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The development of a RFID based leanness monitoring system

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The development of a RFID based leanness monitoring system

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ABSTRACT

Increasing numbers of companies have implemented lean manufacturing because of its proven ability to reduce manufacturing costs and decrease lead times which increase a company's competitiveness. A great deal of time has been spent on development lean tools, which will make systems become leaner. However, significantly less time has been spent developing measurements, which will allow a company to determine how lean a system is. The main focus of this research was to develop a system which would allow companies to determine the lead time of a system, create a value stream map of the system and then predict the leanness of a production system. The development of the system is described in two papers.

The first paper, The Development of an On-Line RFID-Based Lead-time Monitoring System for Value Stream Mapping, proposes a system which allows companies to track their lead times in real-time and then create a value stream map for the system. After successful development of the system it is tested in a laboratory setting to ensure its functionality. Laboratory testing was successful so development of the system continued.

The second paper, The Development of a Leanness Monitoring System via RFID: An Industrial Case Study, proposes a leanness monitoring system (LMS) which allows companies to track their systems leanness in real time. The LMS was run for an extended period of time so that multiple leanness scores can be used to ensure an accurate representation of the production system. Next, kaizen events are held so that the production system can be improved in order to reduce the lead-time. The LMS is then used to determine the leanness score of the production system after the changes were implemented to determine their affect on the system. The resulting leanness scores allowed companies to see how much the changes affected their systems performance while also seeing how much room for improvement there still was.

Chapter 1. General Introduction

1. Introduction

Since its creation in the 1936, the Toyota Production System has altered the way that products are produced and the manner in which they flow through a facility. The main reason for this is because lean manufacturing has established a record of being able to reduce lead-time while also lowering production costs and increasing product quality. Lean manufacturing focuses on using less of everything when compared to mass production and job shop settings. This is accomplished by continuously removing waste from a system. One of the most common tools for doing this is value stream mapping. Value stream mapping is a lean technique used to analyze the flow of materials and information currently required to bring a product or service to a consumer [20].

One of the attributes of a value stream map is the overall lead time. The most popular method for determine lead times is to divide the facilities daily demand for the product by the inventory level at each station. Lead time is defined as the time it takes one piece to move all the way through the process, from start to finish [20]. Therefore, the overall lead time of a system can be used as an indicator of a system's performance and the amount of waste present in a system. Companies can then compare their systems lead times before and after implementing changes to determine what impact the changes had. However, in most push systems there is a high degree of variation in inventory levels at each station, which is caused by the pushing of materials from one station to the next [16].This is an area for concern because most value stream mapping exercises are a one-time event [1]. In addition, the calculations of takt time and quantitative metrics for waste can become out of date quickly if the value stream supports a product line with constant change [1]. Therefore, companies are not able to tell if the reduced lead-time is due to changes they made or normal fluctuations in inventory levels.

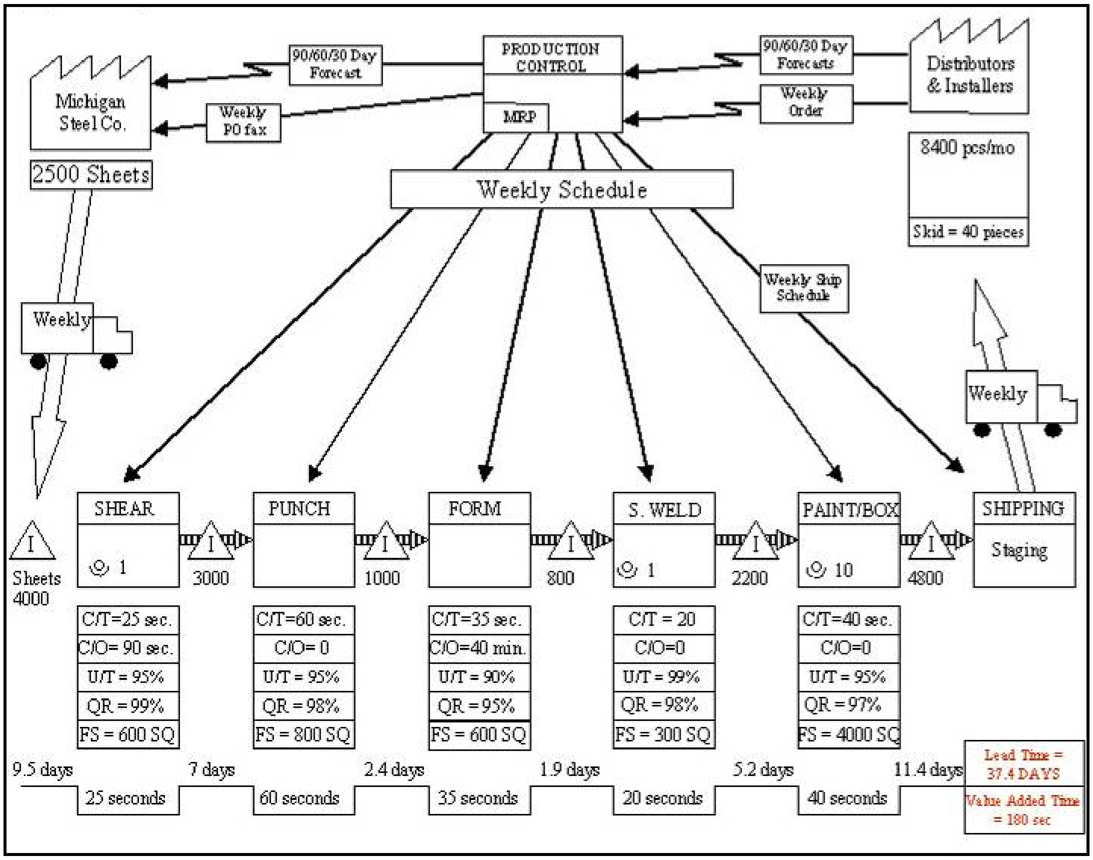

Figure 1. Example Value Stream Map [11]

Ideally, multiple lead times would be calculated over a period of time because more data allows for a better understanding of the system. However, when creating a value stream map a lead time is only calculated one time [1]. This is primarily due to the added labor costs of calculating multiple lead times because the team has to count inventory levels multiple times. This means that there is a high probability that the lead time will be affected by normal fluctuations in inventory.

Even if one is to solve the problem with normal fluctuations in inventory levels; one problem still remains, the fact that moving time is not part of the systems lead time. In some facilities parts are produced in large batch sizes in order to minimize downtime due to changeovers. The large batch sizes are then placed into containers that require a fork truck in order to be moved. When this is the case, moving and storage costs of inventory can be significant and are non-value added [3]. In addition, workers typically have to stop production once a container is full of parts. Assuming the work area has a dedicated material handler; the worker must then find the material handler and ask them to move the full container. Most often, the material handler has a queue of work to do so they will not move the container right away. Finally, once they remove the full container they have to bring an empty container back so the worker can resume production. Therefore, something that initially seems like simple move can easily cost the company half an hour of valuable production time.

The problems with lead times and the lack of moving time show that the current lead time methods need to be improved upon. Therefore, the researchers propose a system which will perform the following:

1. Calculate multiple lead times over an extended period of time so the company can have a better understanding of their system.
2. Monitor the company's lead times allowing managers to see when changes in lead times happen. Therefore they can track the sustainability of improvements because they can easily detect changes in lead times.
3. Require little to no human interaction in order to minimize the cost of determining a system's lead time and creating a value stream map for a production system.
4. Determine the amount of time spent moving a product in the current system and incorporate that time into the systems overall lead time. This allows companies to see the true amount of waste present in their production system.

Keeping these four tasks in mind, the researchers had identified what the successful system should be able to perform. Therefore, the next step was to identify potential technologies which would allow these actions to be performed. Radio Frequency Identification (RFID) was identified as a possible solution because it has been implemented in warehouses to keep track of when an item enters or leaves the warehouse. A more detailed explanation of the RFID system used in this experiment is presented later in this chapter.

2. Thesis Organization

The organization of this thesis is as follows. In the first chapter, the introduction, already discussed, is followed by a literature review and setup of the system. The second chapter, entitled The Development of an On-Line RFID-Based Lead-time Monitoring System for Value Stream Mapping, proposes a system which allows companies to track their lead times in real-time. After successful development of the system it was tested in a laboratory setting to ensure its functionality. Laboratory testing was successful so development of the system continued. The third chapter, entitled the Development of a Leanness Monitoring System via RFID: An Industrial Case Study, proposes a leanness monitoring system (LMS) which allows companies to track their systems leanness in real time. After development of the LMS it was tested in an industrial setting. The LMS was run for an extended period of time so that multiple leanness scores can be used to ensure an accurate representation of the production system. Next, kaizen events were held so that the production system could be improved in order to reduce the lead-time. The LMS was then used to determine the leanness score of the production system after the changes had been implemented to determine the affect they had on the system. Conclusions gained from the research as well as recommendations for future research are then presented in chapter 4.

3. Literature Review

The literature review will be divided into sections for each of the topics that are relevant to the research effort.

1. Current RFID technology in order to select the correct components

2. Development of the lean assessment equation
3. Integrating the hardware to create the On-Line RFID-Based Lead-time Monitoring System

Current RFID Technology in Order to Select the Correct Components

RFID implementation in manufacturing settings is still in its infancy. At this point in time the two main purposes for implement RFID systems are to keep track of tooling, locate inventory and restrict access to certain areas [4],[17], [26]. However, increasing numbers of retailers are requiring their suppliers to attach RFID tags to their shipments [13]. Two-thirds of manufacturers surveyed said they are either implementing or plan soon to implement RFID [2]. RFID systems use wireless radio communication technology to uniquely identify tagged objects. At the most basic level a RFID system is comprised of three main components; a RFID tag, a RFID reader set, and a computer with the appropriate software [13].

Development of the lean assessment equation

The term leanness has been interpreted in many different ways. Naylor et al [18] define leanness as the process of realizing lean principles while introducing the concept of 'leagility'. Comm et al [7] define leanness as a relative measure for whether a company is lean or not. They also stated that leanness is a philosophy intended to significantly reduce cost and cycle time throughout the entire value chain while continuing to improve product performance. In this paper, leanness will refer to the difference between the current manufacturing systems performance compared to the performance of the ideal state of the manufacturing system.

Several researchers have performed studies to find the best way to determine the leanness of a manufacturing system which is summarized below in **Table 1.** There are a wide variety of lean assessment methodologies ranging from self assessment questioners to lean assessment equations with complex mathematical formulas.

Table 1. Past Lean Assessment Research

Year	Author(s)	Title
1996	Karlsson, C., & Ahlstrom, P.	Assessing changes towards lean production
1997	Hines, P. & Rich, N.,	The seven value stream mapping tools
2000	Comm, C., & Mathaisel, D.	A paradigm for benchmarking lean initiatives for quality improvement
2000	Feld, W.	*Lean Manufacturing: Tools, Techniques, and How To Use Them*
2001	Conner, G.	*Lean Manufacturing for the Small Shop*
2001	Jordan, J., Jordan, J., Jr, J., & Michel, F.	*The Lean Company: Making the Right Choices*
2001	Sanchez, A., & Perez, M.	Lean indicators and manufacturing strategies
2001	Tone, K.	A slacks-based measure of efficiency in data envelopment analysis.
2002	Soriano-Meier, H., & Forrester, P.	A model for evaluating the degree of leanness of manufacturing firms
2003	Nightingale, D., & Mize, J.	Development of a lean transformation maturity model
2006	Srinivasaraghavan, J., & Allada, V.	Application of mahalanobis distance as a lean assessment metric
2008	Bayou, M., & De Korvin, A.	Measuring the leanness of manufacturing systems—A case study of Ford Motor Company and General Motors
2008	Wan, H.-D., & Chen, F.	A leanness measure of manufacturing systems for quantifying impacts of lean initiatives

Several lean assessment surveys have been developed, such as Connor [8], Feld [10], and Jordan [14], to guide users through lean implementation. Typically, users self-assess the leanness of their facility by either filling out questioners or benchmarking their company against a company that they feel is lean. The differences between the lean company and the assessors company show how much room for improvement exists. Karlsson and Ahlstrom [15] developed a model to assess the changes of a system towards lean production using nine groups of measureable determinants. Soriano-Meier and Forrester [22] expanded upon this model to assess the degree of leanness in a manufacturing system based upon the company's degree of adoption of nine variables according to the companies self assessment. The nine variables are as follows:

1. Elimination of waste
2. Continuous improvement
3. Zero defects
4. Just in time deliveries
5. Pull of raw materials
6. Multifunctional teams
7. Decentralization
8. Integration of functions
9. Vertical information systems

Sanchez and Perez [21] proposed using a checklist of 36 key lean indicators (shown in **Table 2.**) to assess the company's changes towards becoming lean. Nightingale and Mize [19] propose a methodology, which uses the Lean Enterprise Self Assessment Tool (LESAT). Surveys are used to compare the company's desired state of lean implementation with the company's currents state of lean implementation. The resulting leanness score measures how successful the company has been in reaching their goal. The main problems with these methodologies are:

1. They require sophisticated mathematical computations therefore workers on the plant floor cannot use them.
2. All variables are ideal and actual costs. Although some things, such as labor and overhead, are easily converted to cost other variables, such as lead time, are difficult to convert to a cost. In addition, there is no standard method for converting lead time to a cost.
3. Some companies are unwilling to share cost information with employees for various reasons. Therefore, the results obtained using their proposed methods may not actually represent the true costs.

Table 2. 36 Key Lean Indicators Proposed by Sanchez and Perez [21]

Indicator	Definition
EF1	Percentage of common parts in companies products
EF2	Value of work in process related to sales
EF3	Inventory rotation
EF4	Number of times and distance parts are transported
EF5	Amount of time needed for die changes
EF6	Percentage of preventative maintenance over total maintenance
MC1	Number of suggestions per employee and year
MC2	Percentage of implemented suggestions
MC3	Savings/benefits from suggestions
MC4	Percentage of inspection carried out by autonomous defect control
MC5	Percentage of defective parts adjusted by production line workers
MC6	Percentage of time machines are standing due to malfunction
MC7	Value of scrap and rework in relation to seals
MC8	Number of people dedicated primarily to quality control
EQ1	Percentage of employees working in teams
EQ2	Number and percentage of tasks performed by teams
EQ3	Percentage of employees rotating tasks within company
EQ4	Average frequency of task rotation
EQ5	Percentage of team leaders what have been elected by their own team co-workers
P1	Lead time of customers orders
P2	Percentage of parts delivered just in time by suppliers
P3	Level of integration between suppliers delivery and the company's production information system
P4	Percentage of parts delivered just in time between sections in the production line
P5	Production and delivery lot sizes
I1	Percentage of parts co-designed with suppliers
I2	Number of suggestions made to suppliers
I3	the frequency with which suppliers technicians visit the company
I4	The frequency with which the company's suppliers are visited by technicians
I5	Percentage of documents interchanged with suppliers through EDI or intranets
I6	Average length of contract with the most important suppliers
I7	Average number of suppliers in the most important parts
S1	The frequency with which information is given to employees
S2	Number of informative top management meetings with employees
S3	Percentage of procedures which are written and recorded in the company
S4	Percentage of production equipment that is computer integrated
S5	Number of decisions employees may accomplish without supervisory control

Several tools have been proposed which will allow the leanness of a system to be determined. Srinivasaraghavan and Allada [23] propose using the mahalanobis distance between the current state of the system and a baseline created by benchmarking other companies. Bayou and De Korvin [5] propose using benchmarking along with fuzzy logic to determine how lean a company is. Although these models deliver a quantitative leanness score, they are highly affected by the benchmark results. Additionally, benchmarking is undesirable since no two manufacturing systems are the same due to differences in equipment, people, etc. As with questionnaires, benchmarking is also subjective because the end user selects a company that they feel is lean. Additionally, benchmarking does not tell a company if they are actually a lean company, it only shows whether or not they are leaner than the selected company.

A leanness prediction equation is needed in order to convert the lead times obtained with the ORLMS to a leanness score. The researchers began this process by identifying what others had done in the past and determining the positives and shortcomings of using each methodology. Charnes Cooper and Rhodes [6] proposed the concept of Data Envelopment Analysis (DEA) for performance measurement using a mathematical model, which is shown in **Equation 1**. The Charnes-Cooper-Rhodes (CCR) model is a fractional program that compares the input/output variables of a set of decision making units (DMU) to identify the best practices among them. These DMU's are then used to determine the benchmark for the efficiency score.

$$Max\ h_o = \frac{\sum_{r=1}^{t} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \tag{1}$$

$$\frac{\sum_{r=1}^{t} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{i0}} \leq 1, \quad j = 1,2,\dots,n$$

Where u, v, x and y are all non-negative variables

Notation:

H_o	Efficiency score of DMU_o
X_{ij}	Input Variable i of DMU_j
Yrj	Output variable r of DMUj
n	Number of DMU's
v_i	Weight for input variable i
u_r	Weight for output variable r
m	Number of input variables

t Number of output variables

Tone [24] proposed using a slacks based measure (SBM) of efficiency as shown in **Equation 2**. The SBM is a DEA model that deals with the slacks in the input and output variables. Weights are assigned to λ based upon input excesses and output shortfalls. An efficiency score ρ is then computed that is an invariant valued between zero and one. The resulting ρ represents the system's leanness score.

$$\rho = \frac{1-\left({}^{1}/_{m}\right)\sum_{i=1}^{m} s_i^- / x_{io}}{1+\left({}^{1}/_{s}\right)\sum_{r=1}^{s} s_r^+ / y_{ro}} \quad where\ 0 < \rho \le 1 \tag{2}$$

Subject to:

$$x_o = X\lambda + s^-$$

$$y_o = X\lambda - s^+$$

Where λ, s^+ and s^- ≥ 0

Notation:

ρ	Efficiency score
x_0	Inputs of DMU_0
y_0	Outputs of DMU_0
γ	Weights for DMU's
s^+ and s^-	Slacks associated with inputs/outputs
m and s	Numbers of input/output variables

Realizing that a system can never be 100% lean Wan and Chen [25] altered the model proposed by Tone [24] so that Actual Decision Making Units (ADMU) and Ideal Decision Making Units (IDMU) are used. Their proposed equation is shown in **Equation 3.** Cost and time are the input values used by the equation while values of the DMU's are the output variables. A software solver program was developed to calculate the leanness.

$$Min\ \tau_{lean} = t - \left(\frac{1}{2}\right)\left(\frac{s_T}{x_{TO}} + \frac{s_C}{x_{CO}}\right) \tag{3}$$

Subject to:

$$1 = t + \frac{S_v^+}{y_{vo}}$$

$$tx_{TO} = \sum_{i=1}^{n} X_{Ti} \wedge_i + S_T^-$$

$$tx_{CO} = \sum_{i=1}^{n} X_{Ci} \wedge_i + S_C^-$$

$$tx_{VO} = \sum_{i=1}^{n} X_{Vi} \wedge_i - S_V^-$$

$$t = \sum_{i=1}^{n} \wedge_i$$

$Where\ \wedge, S_T^-, S_C^-\ and\ S_V^+ \geq 0, \quad t > 0$

Notation:

T_{lean}	Leanness score
X_{to}	Input time of DMU_o
X_{co}	Input cost of DMU_o
Y_{vo}	Output value of DMU_o
n	Number of DMU_o
$\wedge$	SBM weights for DMU's
$S_T^-, S_C^-\ and\ S_V^+$	Slacks associated with input/output
t	Multiplier

Lean is not something done in an office; it is something that is done on the floor with workers. With such a math intensive solution the Wan and Chen [25] model is not practical for workers on the plant floor to use. In addition, it is easier for workers to relate to changes in time rather than cost. However, the methodology proposed by Wan and Chen [25] uses costs to calculate leanness. Currently, there isn't a generally accepted method to transfer lead times to costs because it's not as simple as multiplying a labor rate by a time. Furthermore, some companies are hesitant to share cost information with employees for various reasons [9]. Therefore leanness would ideally be measured without requiring cost information.

After identifying currently available methodologies the researchers evaluated them. The positives were then evaluated to see if they could be incorporated into the leanness prediction equation. Next, the shortcomings were evaluated in order to determine if solutions could be made and then incorporated into the leanness prediction equation. This paper presents a simplified version of the methodology used by Wan and Chen [25] because the researchers thought the current formula was too complicated to be used in smaller manufacturing facilities. In addition, the researchers wanted to use variables that were easier to obtain sin order to increase the probability that companies would use the equation. The top of the proposed equation, shown in **Equation 4,** is set up in a similar way to the formula proposed by Wan and Chen [25]. The main difference is that the variables were changed to ones that were easily obtainable in a real world setting. The other difference between the equations is that the proposed equation was expanded further so that undesirable conditions were taken into account in the denominator. Therefore, undesirable conditions in the system decrease the systems leanness score, the more prevalent the condition the more it decreases the leanness score. The proposed leanness equation focuses on the wastes present in the current system. Under ideal conditions, a one piece flow system, the lead time of an operation would equal the systems processing time. Once again, using a one piece flow system as a point of reference, the ideal inventory level is one piece in each work station. Therefore γ and ω are calculated as the percentage of lead time and inventory that are considered wasteful. The bottom portion of the equation focuses on undesirable outputs of the current system, which in this case are defects. Therefore, ρ is the defect rate which is ideally zero.

$$Leanness = \frac{1 - \frac{1}{2}(\gamma + \omega)}{1 + \rho} \tag{4}$$

Notation:

$$\gamma = \frac{\sum Lead\ Time - \sum Processing\ Time}{\sum Lead\ Time}$$

$$\omega = \frac{\sum Inventory\ Levels - \#\ of\ Stations}{\sum Inventory\ Levels}$$

$$\rho = Defect\ Rate$$

Using the proposed equation the ideal leanness score of any system is 1. However, since that can only be attained when a company uses a one piece flow system with no defects, it is highly unlikely that a system will receive a leanness score one. When testing the equation the leanness score decreased very rapidly when the lead time and inventory levels in γ and ω increased to the point where they had ratios of four to one. When the lead time and inventory levels used in γ and ω increased so that ratios greater than four to one the leanness score started to decrease at a much lower rate. Since these ratios are low compared to what is typically seen in manufacturing facilities it is likely that companies will receive a leanness score of 0.100 or less.

Integrating the RFID hardware

RFID systems can consist of many readers spread across a work area or an entire facility [6]. The RFID system used in this case study uses four readers to monitor four different storage areas. Careful consideration was taken when selecting the components to ensure that they would be able to work in a wide range of manufacturing settings including metal rich and water rich environments. The following components were selected for the RFID system.

- Texas Instruments 251B Low Frequency RFID Reader
- Large Series 2000 Gate Antenna
- Elenco DC Power Supply
- 85mm RFID Disk Tags

As shown in **Table 1**, low frequency RFID readers perform the best in metal and water rich environments when compared to the out of the currently available reader frequencies. Therefore a low frequency was selected because it would function well in a wide range of conditions. However, they typically have a read range of two feet or less so a large gate antenna and large RFID tags were chosen to maximize the systems read range. In addition, monster cable was used because the manufacturer stated that it would allow the system to achieve its maximum read range. Once the components were selected they were connected as shown in **Figure 2.**

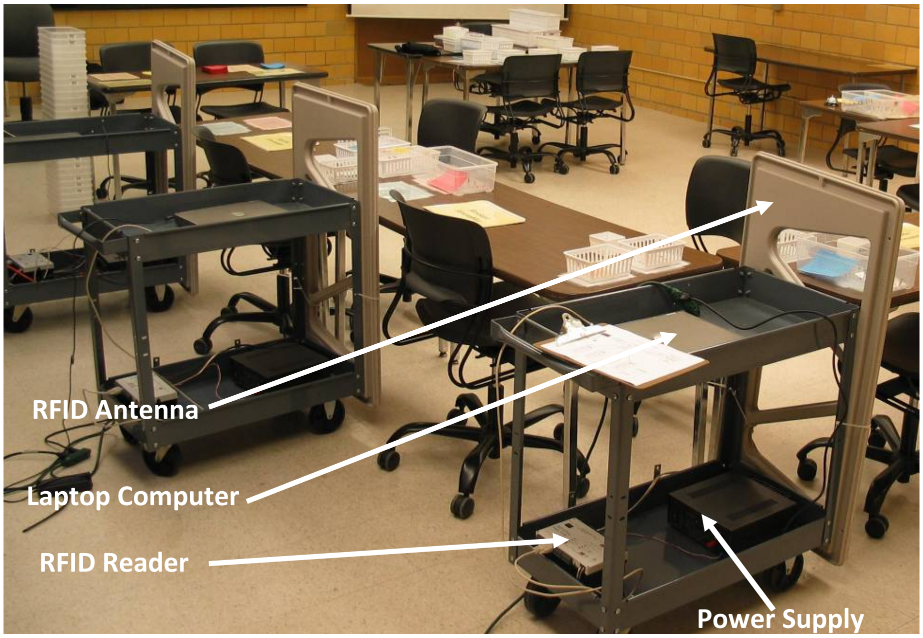

Figure 2. Hardware Integration Diagram

Summary

In this literature review current RFID technology was reviewed, a literature review for the leanness equation was performed and the RFID hardware was integrated into the proposed on-line RFID based leanness monitoring system (ORLMS). An ORLMS was proposed which allows companies to determine a products lead time and then generates a value stream map based upon the lead time. Then a leanness prediction system was proposed which allows companies to determine how lean their facility is and how much their system can be improved. After completing the literature review the desired components had been identified for a successful RFID system. The experimental setup, conclusion, and results will be discussed in greater detail in the following chapters.

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CHAPTER 2: THE DEVELOPMENT OF AN ONLINE RFID-BASED LEAD-TIME MONITORING SYSTEM FOR VALUE STREAM MAPPING

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Abstract

Value stream mapping is a lean technique used to analyze the flow of materials and information currently required to bring a product or service to a consumer. This paper presents the development of an online RFID-based lead-time monitoring system (ORLMS) which is used to generate lead times for a value stream map. More importantly, the ORLMS allows for online data collection and lead-time generation in real time. Having multiple lead-time measurements ensures that the results are not affected by abnormal inventory levels at the time the map is drawn. The ORLMS is then tested in a simulated facility that produces two products simultaneously. The facility layout is also changed from a job shop layout to a cellular layout to ensure that reader collision is not a problem. Once testing is completed, a value stream map is created for each product in both of the environments.

Introduction

Since its creation in 1936, the Toyota production system has altered the way that products are produced and the manner in which they flow through a facility. The main reason for this is because lean manufacturing has established a record of being able to reduce lead-time while also lowering production costs and increasing product quality. Lean manufacturing focuses on using less of everything when compared to mass production and job shop settings. This is accomplished by continuously removing waste from a system. One of the most commonly used lean tools is value stream mapping [20].

Value stream mapping is a lean technique used to analyze the flow of materials and information currently required to bring a product or service to a consumer [19]. There are two types of value stream maps: the current map and the future map. The current map represents the current condition of the system, while the future map shows the ideal condition of the system. The process begins with defining the product that will be value stream mapped. Next, a team of engineers, workers, managers, and suppliers is formed. This ensures that the team has the knowledge to solve most problems that become apparent throughout the process. The team begins by touring the facility, starting in the raw material storage area and ending in the shipping area. This allows the team to become familiar with the current process.

Although value stream mapping is a very useful lean tool, there are several problems with current methods. In most push systems there is a high degree of variation in inventory levels at each station, which is caused by the pushing of materials from one station to the next [7]. This high degree of inventory variation causes a variation in lead times because current methods calculate lead time based upon inventory levels at each station [19]. In addition, value stream maps are typically only drawn one time because creating a value stream map requires a great deal of time and effort [future solutions].

With the high degree of variation in lead times, it would be very easy to draw a value stream map that does not truly represent the system because inventory levels are abnormally low or high [1].

Value stream maps can be used to show the effects that lean activities have had on a system by comparing the current lead time with previous lead times. However, with the high degree of inventory variation in the system, it is hard to tell if the reduced lead time is due to the lean activities, abnormally high inventory levels at the time the map was drawn, or abnormally low inventory levels at the time the map was redrawn. Because of this, if the system was improved the new value stream map could show that the system is now worse than it was before. Therefore, multiple value streams need to be made to ensure that the lead-time changes are caused by the lean actions and not variation in inventory levels.

In addition to the high degree of variation in inventory levels, value stream maps are unable to account for moving time and delays. Moving and storage costs of inventory can be significant and are non-value added [2]. Moving time is not only the amount of time that is required to move the product, but also the time that a product spends in an inventory area while waiting to be moved. With delay time included, a move that takes a couple minutes can easily end up taking several hours. Therefore, moving time can be a significant waste that is not identified when creating a value stream map.

Inventory level variation and moving time need to be accounted for in a value stream map. An automatic system needs to be developed that allows companies to collect this valuable information while also requiring minimal employee interaction. Since there is a high degree of variation in lead times, the ideal system would also allow for online lead-time data collection and storage.

The rest of this paper will be organized as follows: A literature review is performed in section 2. The experimental setup for testing will be presented in section 3. Section 4 will describe how the system was tested in two different environments and the results of each test. Conclusions will then be summarized in section 5.

Literature Review

When tracking objects throughout a facility, companies have many options to choose from. The most commonly used methods are bar codes and RFID tags. Although bar codes have been used for the past several decades, they are quickly losing ground to RFID systems [12]. The main disadvantage of using a bar-code system is that a reader must scan each individual item. In addition, if the bar code is dirty the bar-code scanner will not be able to read the bar code [10].

In contrast, an RFID system can detect several RFID tags at a time. Therefore, if there were 20 boxes of parts on a pallet, all 20 tags could be scanned at one time, which reduces the amount of labor involved in tracking the parts. The main advantage of using RFID is that it does not require direct contact or line-of-sight scanning [4]. This means that, unlike the bar-code system where a bar-code reader must scan boxes, the RFID tags can be several feet away from the antenna and be read by the RFID reader.

Although RFID systems have several advantages over bar-code scanning, there are two main drawbacks: read range and misreads [17]. Read range is the maximum distance a tag can be away from the antenna and still communicate with the antenna. Companies typically add additional RFID readers and antennas in order to increase the areas where tags can be read. A misread occurs when the RFID system falsely says a tag is present or absent.

Many companies currently use RFID systems to track parts through their facilities because they have found them to be more efficient than manually searching for parts [11]. Additionally some companies, such as Wal-Mart, have started requiring their suppliers to attach RFID tags to all their shipments. This has in turn has driven the costs of RFID systems lower and lower, which has caused more companies to install RFID systems in their facilities.

Although increasing numbers of companies have implemented RFID systems, they have yet to be used to create value stream maps. This paper will show how an RFID system can be used to assist with the creation of a company's value stream map in an efficient manner with little human interaction required. By using the proposed RFID value stream mapping method, companies would be able to see how the lead time of the system is changing in real time. Real-time data acquisition also allows the company to account for more variation in the production process.

How to Create a Current Value Stream Map

Value stream mapping is a lean tool that has been used for several years because it allows people to "see" some of the wastes that are present in any system. The most popular value stream mapping was proposed by Rother and Shook in their book, *Learning to See [19]*. In this method, the lead time for each operation is based upon the facility's daily demand. The main drawbacks to using this method are that it does not account for material handing time and inventory levels vary.

The proposed methodology will allow the user to get the actual lead time for each operation. However, it will not generate an entire value stream map. Therefore, the value stream map "template" will need to be created by the user. To assist with that, the following example will walk through the steps required to make a value stream map using the Rother and Shook [19] methodology. Each of the numbers before each step corresponds to a numbered circle on the example value stream map shown in **Figure 1**.

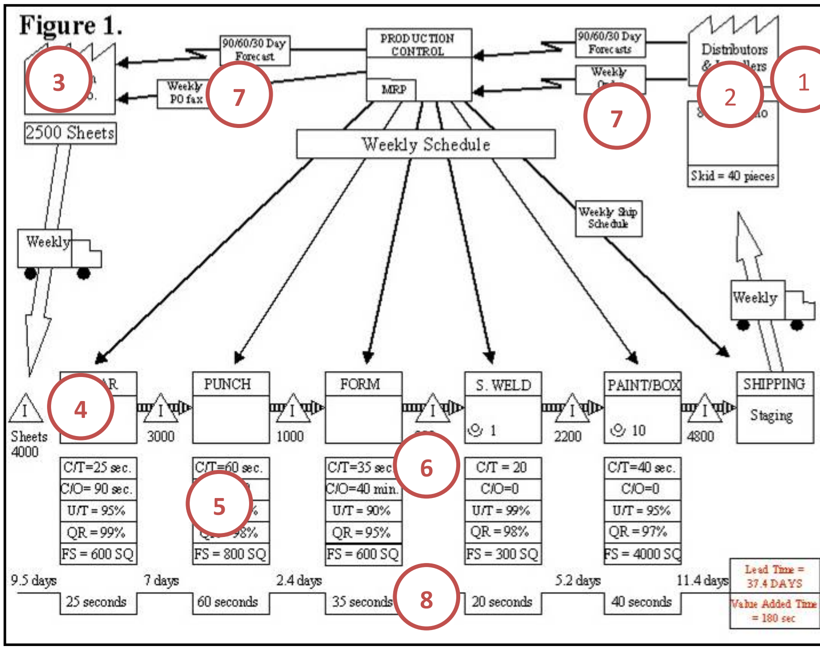


Figure 1. Example of a value stream map [5].

1. Define the customers takt time (TT) and daily demand (DD), which is calculated as follows:

$$TT = \frac{Available\ Time}{Yearly\ Demand} = \frac{450\,\frac{Minutes}{Shift}\ x\ 20\,\frac{Shifts}{Year}}{8{,}400\,\frac{Pieces}{Month}} = 1.07\,\frac{Minutes}{Piece}$$

$$DD = \frac{Monthly\ Demand}{Working\ Days\ per\ Month} = \frac{8{,}400\,\frac{Pieces}{Month}}{20\,\frac{Days}{Month}} = 420\,\frac{Pieces}{Day}$$

2. Draw the customer symbol in the upper right-hand corner of the paper. Next, add in information about the customer such as the takt time, yearly demand, and batch size.

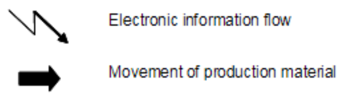
3. Draw supplier information in the upper left-hand corner of the paper. Make sure to note the frequency of deliveries and minimum order quantity.

4. Draw process boxes for each of the operations along the bottom third of the piece of paper. Make sure to leave enough room so that a timeline can be drawn below them.

5. Add the number of workers, cycle time, changeover time, and uptime to each operation box. Then draw inventory symbols between each operation and record the amount of inventory present at each station.

6. Note whether the products are being "pushed" or "pulled" to the next process. Push means that a process is producing parts regardless of whether or not they are needed. In contrast, pull means that parts are being produced as they are needed.

7. Draw in information flow for the system using the icons shown below. This includes production scheduling, customer orders, and supplier orders.



8. Add the time line to the bottom of the page. The top portion of the time line shows the lead time of each operation. If the inventory level of the station is 500 pieces and the daily demand is 60 pieces, the daily demand is calculated as follows:

$$LT = \frac{Inventory\ Level}{Daily\ Demand} = \frac{500\ Pieces}{60\,\frac{Pieces}{Day}} = 8.33\ Days$$

After the lead times have been calculated and added to the map, it is time to add the "value added" time to the map. The amount of value added time for each operation equals the operations processing time because it is the amount of time that a worker spends making the part. After adding the value added time to the time line, the final step is to sum the lead time and the processing time. This information is then added to the right of the time line. When finished, the value stream map will resemble the example shown in **Figure 1**.

RFID Technologies Currently Available

An RFID system, as shown in **Figure 2**, is comprised of a tag, a reader set, and a computer with the appropriate software [6]. The RFID tag and interrogator (reader) communicate with each other through radio waves. When a tagged item comes within the read range of the reader, the reader tells the tag to transmit whatever information it has stored on it. Once the reader has received the information, it is sent to the computer. This can be accomplished by using cables or using a wireless transmitter. The computer then uses its onboard software to process the information and perform desired operations. The computer then displays the information in a manner that can be easily read by the user.

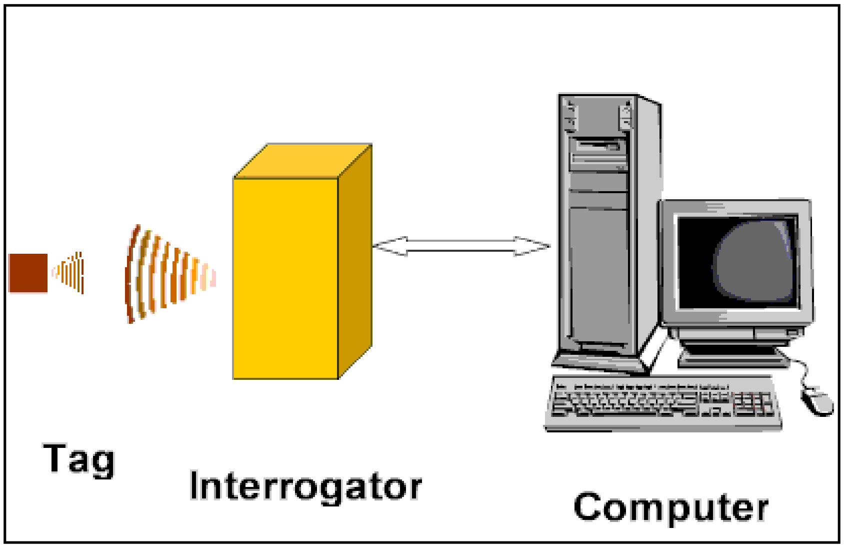


Figure 2. RFID system diagram [18]

RFID systems can consist of many readers spread across a work area or an entire facility. All of the readers in a system can be connected through a network so that only one computer is required. Depending on the reader being used, it can communicate with up to 1,000 RFID tags per second with an accuracy of more than 98% [15].

Current Uses for RFID Systems

Although the idea for an RFID system was thought of early on, it did not start to become a reality until the 1970s. At that point in time, development was focused on using RFID systems to track animals, track automobiles, and automate factories. In the late 1980s, RFID systems were mainly used in the United States to collect tolls. With continued technology advancement in the 1990s, RFID systems began to be used for more and more applications. RFID implementation began to skyrocket when the U.S. Army required their suppliers to place passive RFID tags on all items sold to them. Walmart asked their top 100 suppliers to attach RFID tags to all of their products by the end of 2005 [8]. Today RFID systems are used to do a wide variety of tasks, some of which are shown in **Table 1**.

Table 1. Current uses for RFID systems. [9]

User	What RFID Is Used For
Retailers	Track pallets coming in and going out of a facility Speed-pass systems for quicker check-out times Theft preventative systems
Police	Keep track of testing samples in crime labs
Hospitals	Keep track of patient records
Farmers	Track cattle and manage vet records
Meat Packers	Track meat back to the cow it came from, including hamburger
States	Pre-pay tolls to ease congestion

RFID Tags Currently Available

The basic function of the RFID tag is to store and transmit data to the reader. RFID tags are a combination of a small radio frequency chip attached to a microprocessor, and they range in size from as small as a pinhead to as large as a human palm. RFID tags can typically be grouped into one of three main types: active, passive and semi-passive. The attributes of each tag are shown below in **Table 2**.

Table 2. Attributes of different types of RFID tags. [9]

<table>
<tr><th></th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Passive</td><td>• Longer life time
• Wider range of form factors
• Tags are more mechanically flexible
• Lowest Cost</td><td>• Read range of 4-5 meters
• Strictly controlled by local regulations</td></tr>
<tr><td>Semi-Passive</td><td rowspan="2">• Greater communication distance
• Can be used to manage other devices like sensors (temp, pressure, etc.)
• Do not fall under the same strict power regulations as passive devices</td><td rowspan="2">• Expensive due to battery and tag packaging
• Reliability: Impossible to determine whether a battery is good or bad
• Widespread proliferation of active transponders presents an environmental hazard from potentially toxic chemicals in batteries</td></tr>
<tr><td>Active</td></tr>
</table>

Information stored on the tag typically includes a tag identification number and other desired information such as the size, weight, and quantity of items inside the tagged package. The information stored on the tag is only sent to the reader when the reader receives a command to retrieve the data [16]. Tags are typically placed on the outside of a package or pallet of merchandise so that large numbers of products can be tracked at once.

For any of the RFID tags, the end user must choose which type of memory the tag utilizes. This choice not only affects what can be done with the tags, but it also affects the cost of the RFID tags. Each RFID tag contains portable memory, which is either read-only or read/write. Both types of tags have the ability to be read by the RFID reader. The main difference between the two tags is that read/write tags have the ability to have information written to them on the fly by the RFID reader [21]. This causes read/write tags to have larger amounts of memory, which makes them the more expensive option.

RFID Tags That Will Be Used in the Experiment

As mentioned earlier, the RFID system will be used to track items as they travel through a system so that the lead time can be determined. The tag's location will be continuously sent to a computer where it will be recorded. Therefore, it will be unnecessary to write information on the tags while they are traveling through the system. Finally, disk tags were chosen because they will allow for a longer read range.

RFID Readers That Are Currently Available

The RFID reader needs a constant supply of DC power in order to function correctly. Once the system has power, the reader set is used to transmit information to the tags and receive data from the tag. The reader communicates with the tag through the antenna, which is also used to supply passive RFID tags with enough power to communicate with the reader. In addition, the RFID reader system also performs the following functions:

- Receives commands from the user through a computer and sends back the desired information
- Converts radio waves into digital information so that computers can understand the information coming from the tag

Currently there are four different frequencies of RFID readers, which are shown below in **Table 3**. As the table shows, the frequency not only has an effect on the read range of the system, but also the reader's ability to read in metal/water-rich environments as well as the size of tags used by the system.

The Reader System That Will Be Used in the Experiment

When the system was created, the researchers envisioned a system that could be used in a variety of local metal manufacturing facilities. As mentioned earlier, a low-frequency system would perform best in this type of environment. After comparing several different readers, the Texas Instruments S251B low-frequency reader was chosen. Since low-frequency readers have a small read range, a large series 2000 gate antenna was chosen to increase the read range of the system.

Table 3. Comparison of RFID Bands Currently Used [8]

Band	Low	High	Ultra High	Microwave
Frequency	125–134 KHz	13.56 MHZ	860–930 MHZ	2.5 GHz and above
Typical Read Range	<0.5m	~1m	4-5m	~1m

Reading around Metals and Liquids	Better ⟷ Worse
Multi-Tag Read Rate	Slower ⟷ Faster
Passive Tag Size	Larger ⟷ Smaller

Experimental Setup for Testing the Online RFID-Based Lead-Time Monitoring System

The Online RFID-Based Lead-Time Monitoring System (ORLMS) is an RFID system that is used to monitor the lead time of items as they flow through a facility. An operational diagram for the ORLMS is shown in **Figure 3**. When a tag enters the read range of the antenna, the developed program records the date, time, and tag identification number into an Excel spreadsheet. The program keeps collecting data until the tag leaves the read range of the antenna. This is done to ensure that the results are accurate because on occasion the reader will get a false negative reading (beta error) or a false positive reading (alpha error). A false negative reading occurs when the reader tells the computer a tag is not present when the tag is actually present. In contrast, a false positive reading occurs when the reader tells the computer a tag is present when it is no longer in the area. After testing is completed, a person determines the lead time for each of the tags by manually calculating the number of working days, hours and minutes that passed while the parts were in a specific inventory area. Sometimes a product was moved from one inventory area to another before being worked on. In this case, the lead times for both inventory areas were combined to create a single lead time. This process was repeated until the lead time for all the inventory areas had been calculated.

The ORLMS was tested using the Lean 101 training kit developed by NIST to teach manufacturing employees the basics of lean manufacturing [13]. During Lean 101 training, the participants work for Buzz Electronics, a simulated company that manufactures security devices. The company manufactures two models, the Blue Avenger and the Red Devil, at the same time in their facility. To ensure that orders are completed in a timely manner, orders are made on a first-in-first-out basis.

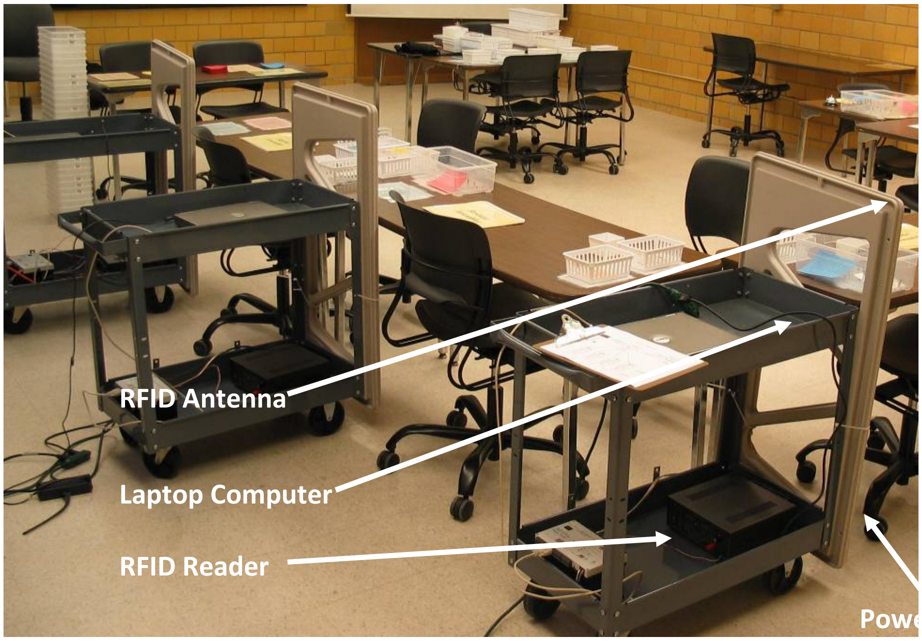
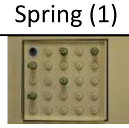
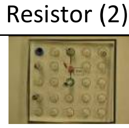
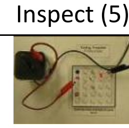
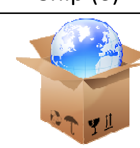


Figure 3. Diagram of the ORLMS.

Blue Avenger Manufacturing Information

The process of manufacturing a Blue Avenger involves six operations, which are summarized in **Table 4**. Manufacturing begins when five springs are inserted into the board. Next, the parts are taken to the resistor area where one red resistor is installed on the board. The parts are then taken to the diode area so that two diodes can be installed on the board. After the diode assembler is finished, the parts are placed in an outgoing area and then transported to the LED area. One LED is then installed on the board, and the board is now completed. The completed board is then taken to the inspector to ensure that the board functions properly. Testing the board ensures that the LED and diodes are oriented in the correct manner. Boards that fail inspection are reworked and tested again until they pass. Once all the parts are deemed good, they are taken to the shipping area and sent to customers.

Table 4. Process at a glance for the Blue Avenger.

Process	Spring (1)	Resistor (2)	Diode (3)	LED (4)	Inspect (5)	Ship (6)
Picture						
Cycle Time	17 sec	14 sec	19 sec	10 sec	10 sec	5 sec
Inspection Tools	Template	Template	Template	Electric tester	None	None
Fixture	None	None	None	None	None	None

Red Devil Manufacturing Information

Red Devils are manufactured in almost the same manner as the Blue Avengers with one main difference: there are no diodes on the product (see **Table 5**). The Red Devil requires three resistors instead of using one resistor and two diodes.

Table 5. Process at a glance for the Red Devil.

Process	Spring (1)	Resistor (2)	LED (3)	Inspect (4)	Ship (5)
Picture					
Cycle Time	17 sec	25 sec	10 sec	10 sec	5 sec
Inspection Tools	Template	Template	Template	Electric test	None
Fixture	None	None	None	None	None

Testing the ORLMS

After creating the RFID system, the researchers needed to be sure that the system would function as desired. Therefore, the system was tested in a laboratory setting in order to allow a controlled environment. The laboratory setting also allowed the researchers to change the facility layout from a job shop to a cellular design in a matter of hours rather than weeks or months. Changing the layout enabled the researchers to test the equipment in two very different environments in a short period of time.

In most job shop settings, machines are grouped together by the tasks that they perform [3]. This leads to the formation of distinct departments throughout a facility, such as the press department or the forming department, which, in turn, means parts travel across the facility so that they can have all of the needed operations performed on them. Parts are typically moved in large batches so that the moving time can be spread across several parts rather than a single part. In contrast, a cellular layout has all the machines required to make a product arranged together. Since the machines are relatively close to each other, workers are able to carry parts to the next operation, which minimizes the need for a material handler.

During the simulation, 12 participants performed tasks ranging from assembly operations to material handling. If the system were implemented in a real-world manufacturing facility, the employees would have an intricate knowledge of the process. However, many of the participants had not preformed their assigned tasks before. This required the researchers to do two things to ensure that the data was not affected by the participants' lack of knowledge. First, the participants were given full-size templates, which showed exactly where their components went on the boards. The participants were then given 20 minutes to practice their jobs before testing began.

Many facilities have inventory or work in process (WIP) present. However, in the simulation there was a very small amount of inventory when the simulation began. Therefore, if one was to collect during the beginning of the simulation, all of the process lead times would be either zero seconds or near zero. To ensure this didn't affect the results, the simulation was run for 10 minutes before collecting data to ensure a steady-state condition. This amount of time was chosen because researchers noticed that inventory levels began to plateau after about five minutes. Five containers of red boards with RFID tags and five containers of blue boards with RFID tags were run through the system.

As mentioned earlier, the ORLMS outputs the lead time of each operation in real time as items move through the system. If run for an extended period of time, a large amount of data becomes available. Over a long enough period of time, the data becomes normally distributed, which allows companies to do various kinds of statistical analyses. Companies can then set up confidence intervals for the data so that they can quickly determine when abnormally long lead times or moving times are occurring so that the situation can be addressed. In addition, companies can determine the standard deviation of moving time and lead time to determine how stable their current process is. Although these are both possibilities, they were not done in this paper because five data samples were taken and they were not normally distributed and had a high variation.

In order to get the lead times to a value stream map, the user must create a value stream "template" for each product. Using the steps previously described a value stream map template was made for the Blue Avenger (**Figure 4**) and the Red Devil (**Figure 5**). Each of the letters surrounded by a circle represents a lead time that will need to be filled in with the results from the ORLMS.

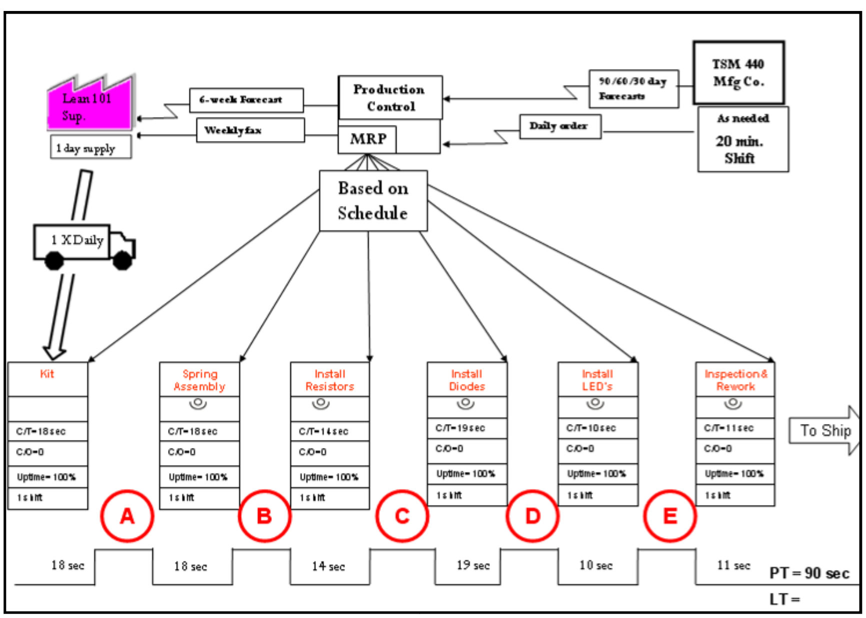


Figure 4. Blue Avenger value stream map template.

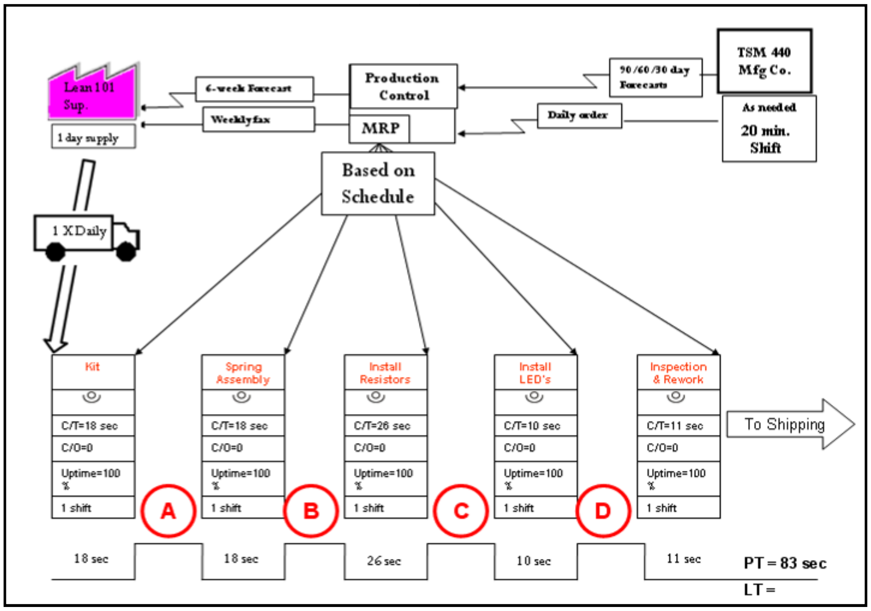


Figure 5. Red Devil value stream map template.

Since the ORLMS outputs lead times in real time, the end user has several options of what to do with the numbers. All of the numbers that are output by the ORLMS represent what is actually happening at that point in time; therefore, a value stream map can be made with the most recent results. However, since there is a large amount of variation in lead times, the researchers decided to use the average of the five lead times obtained for each operation when creating the final value stream map.

Testing and Results of the ORLMS in a Job Shop

As mentioned previously, the ORLMS was tested in a job shop to ensure that it would function as desired. The layout for the job shop simulation is shown in **Figure 6.** The circles represent Red Devil operations, while the squares represent Blue Avenger operations. The numbers inside each of the shapes represent each operations number in the overall sequence of operations. Since the stations are spread apart, a material handler was required to move parts from one operation to the next.

Results for the ORLMS in a Job Shop Environment

After setting up the job shop environment, as shown in **Figure 6**, testing began. The first tagged box was not run through the system until 10 minutes had passed to ensure that each operation had inventory. A tagged batch of Blue Avengers was the first box that was run through the system. Once the batch of Blue Avengers reached the shipping area, a tag was placed on the next order of Red Devils. Tags were placed on alternating batches of products in the same manner until five batches of each product were run through the system. After the simulation was completed, the researchers interpreted the results and put them in two different tables, one for the Blue Avenger (**Table 6**) and one for the Red Devil (**Table 7**). To make the tables easier to read, each operation's lead time and moving time were combined together.

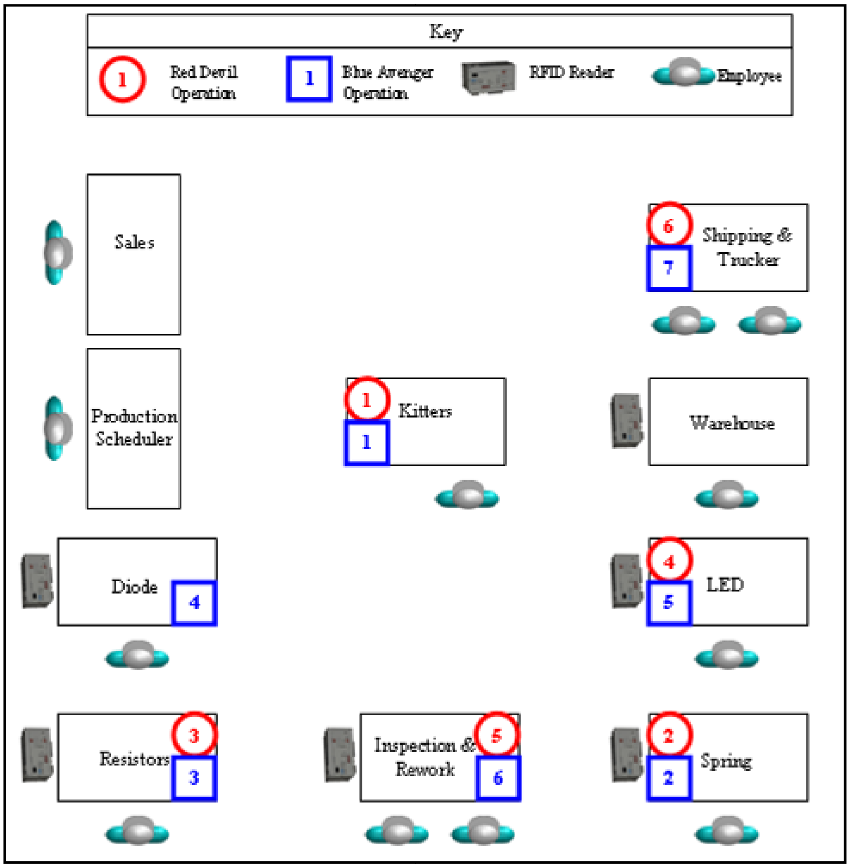


Figure 6. Job shop layout with order of operations for Blue Avenger and Red Devil.

While watching the workers perform their tasks, several observations were made. Workers started out working very quickly, and low amounts of inventory were present before each operation. However, as time went on and some workers slowed down, inventory levels between stations began to increase. Some of the workers panicked and began to work faster when inventory levels before their station began to increase. This then caused inventory levels to become higher at the station after their process.

After creating **Tables 6 and 7**, the next step was to make a value stream map for each of the products using the data. Since there was a wide range in operation lead times, the average lead time for each operation was used. The resulting value stream map for the Blue Avenger is shown in **Figure 7**, while the value stream map for the Red Devil is shown in **Figure 8**.

Table 6. ORLMS lead-time results for Blue Avenger in the job shop setting.

Lead Time (seconds)						
Board	Process					Total Lead Time (sec)
	A	B	C	D	E	
1	369	329	19	206	13	936
2	310	418	13	187	17	945
3	258	126	15	82	16	497
4	526	174	20	15	12	747
5	450	343	12	24	13	842
Average	383	278	16	103	14	793

* A, B, C, D, and E can be found in **Figure 7.**

Table 7. ORLMS lead-time results for Red Devil in the job shop setting.

Lead Time (seconds)					
Board	Process				Total Lead Time
	A	B	C	D	
1	21	192	15	14	242
2	323	15	344	39	721
3	439	351	327	11	1128
4	298	19	360	12	698
5	176	115	322	17	630
Average	251	138	274	19	682

* A, B, C, and D can be found in **Figure 8**.

The simulation showed that the ORLMS would function in a job shop environment. Multiple lead times were obtained for each product and the products moving time was able to be incorporated into the overall lead time. In addition, the results of the simulation showed that there was a high degree of lead-time variation in each of the operations. After concluding that the simulation would work in a job shop, the next step was to test the system in a cellular layout.

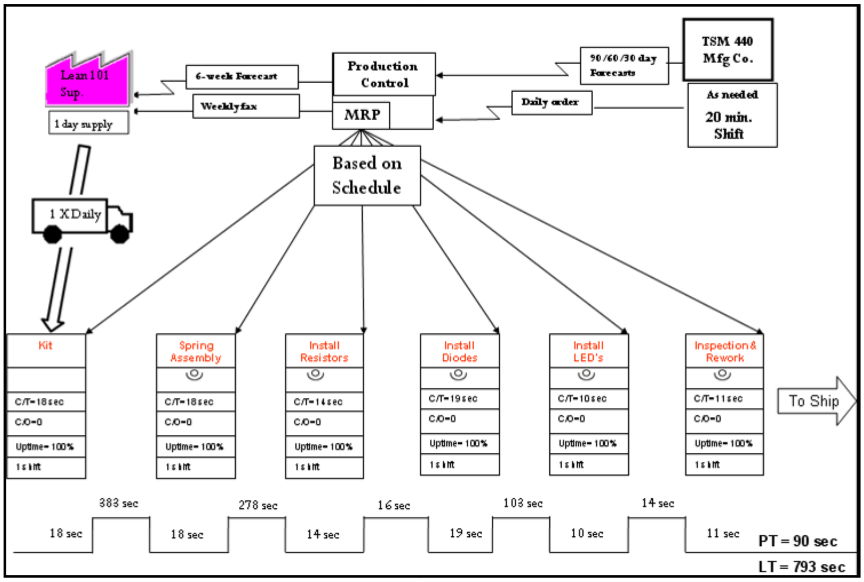


Figure 7. ORLMS value stream map for Blue Avenger in job shop setting.

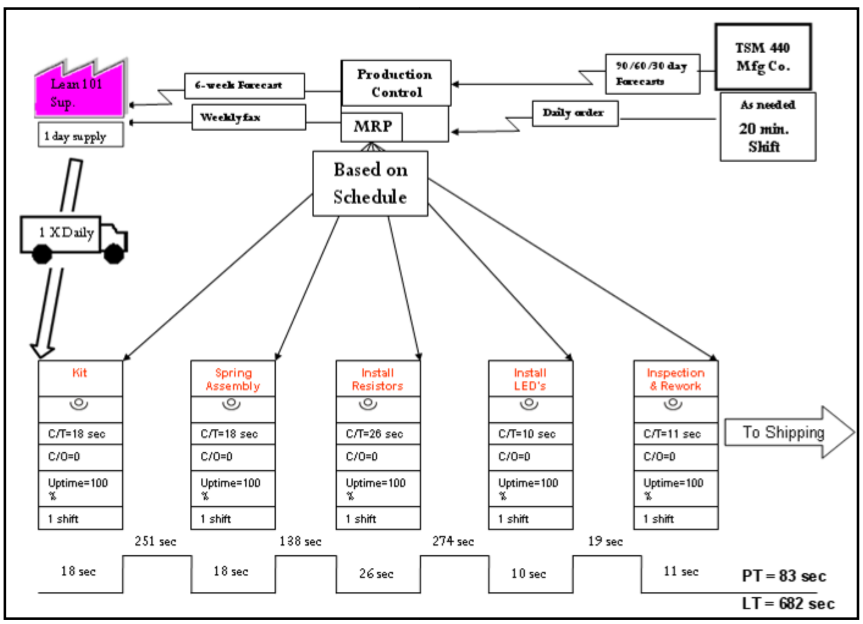


Figure 8. ORLMS value stream map for Red Devil in job shop setting.

Testing and Results of the ORLMS in a Cellular Layout

Although job shop settings are still the most prevalent manufacturing environment, more and more companies have begun to implement lean manufacturing principles in their facilities [14]. Therefore, the second simulation was performed in a simulated cellular layout (shown in **Figure 9**), which could be seen in a facility that has implemented lean manufacturing principles. The main challenge in implementing an RFID system in a cellular environment is that the operations are relatively close to one another. When

RFID antennas are placed close together, they tend to interfere with one another. This can result in a tag being read when it is not present or a tag not being read when it is present.

The processes and order of operations for the cellular layout are the same as they were in the job shop environment. However, a few changes were made to the way that the parts are produced. A material handler is not required to move parts from one station to another because the operations are close enough to each other that the operators can pass the parts to the next operation. In addition, the batch size for the cellular design is half of what it was in the job shop. Therefore, Red Devils are made two at a time while Blue Avengers are made three at a time.

As in the job shop setting, the simulation began after the layout was changed so that it now looked like **Figure 9**. The first tagged box was not run through the system until the workers had been producing parts for 10 minutes to ensure that each operation had inventory. The first box of tagged parts that was run through the system was a batch of Blue Avengers. After the batch of parts reached shipping, a tagged batch of Red Devils was run through the system. Alternating batches of tagged parts were run through the system until five tagged batches of parts were run through the system. After the simulation was completed, one of the researchers interpreted the results and determined the lead time for each batch. The results were then compiled into two tables—one for the Blue Avenger (**Table 8**) and one for the Red Devil (**Table 9**).

After the tables were created, the next step was to use the lead times from the ORLMS to draw a value stream map for each of the products. The value stream map templates created in section 2 were used for this task. The resulting value stream map for the Blue Avenger is shown in **Figure 10**, while the value stream map for the Red Devil is shown in **Figure 11**.

Table 8. ORLMS lead-time results for Blue Avenger in a cellular layout.

Lead Times (seconds)						
	Process					Total Lead Time
Board	A	B	C	D	E	
1	84	16	69	28	18	215
2	58	70	47	64	11	250
3	104	91	66	15	12	288
4	172	179	167	23	19	560
5	187	250	346	10	17	810
Average	121	121	139	28	15	425

*A, B, C, D, and E can be found in **Figure 7**.

Table 9. ORLMS lead-time results for Red Devil in a cellular layout.

Lead Times (seconds)					
	Process				Total Lead
Board	A	B	C	D	Time (sec)
1	64	90	98	19	271
2	102	74	50	17	243
3	133	132	16	14	295
4	237	191	12	21	461
5	121	102	15	11	249
Average	131	118	38	16	304

* A, B, C, and D can be found in **Figure 8**.

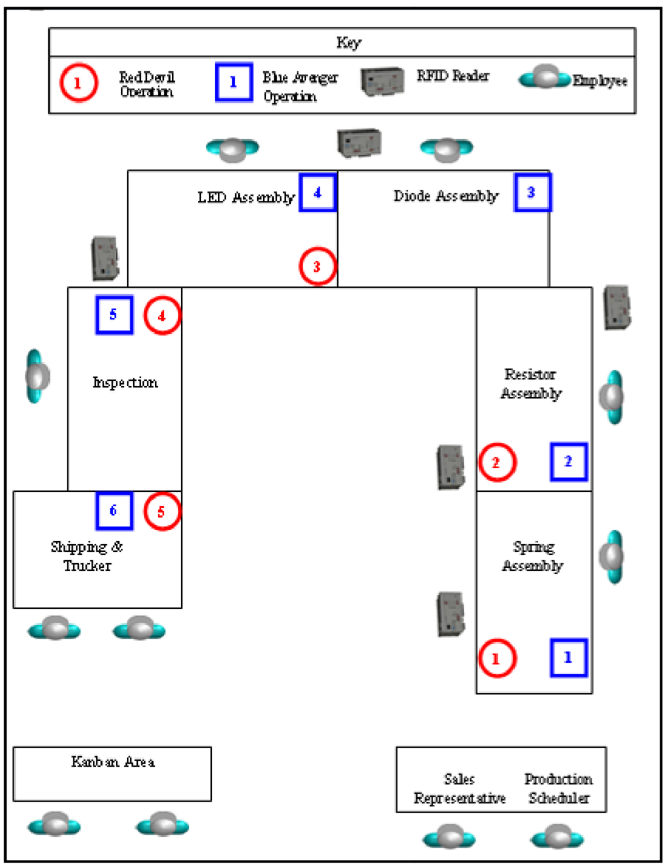


Figure 9. Cellular design layout with order of operations for Blue Avenger and Red Devil.

Several observations were made during testing in the cellular layout. In addition to the smaller lead times, workers seemed to be less stressed than they were in the job shop setting. This was due to each station having smaller inventory levels. Therefore, workers no longer panicked when inventory increased. One key improvement was that there were no longer delays associated with workers having to wait for a material handler to arrive and carry their parts to the next station, which affected the lead times of several operations.

Lead time C for the Blue Avenger jumped from 16 seconds in the job shop to 139 seconds in the cellular design. The primary cause for this was that after removing the material handler from the system operations, A and B no longer had long delays associated with waiting for the material handler to pick up parts. This caused their lead times to be reduced by about 50% and shifted the bottleneck to operation C, which had the longest processing time.

The simulation showed that the ORLMS could be implemented in a cellular layout without having problems with reader collision. Testing also showed that if readers are placed closer than five feet from each other, collision becomes a problem that needs to be addressed. In addition, the results in **Tables 8 and 9** show there is still variation in lead times for the cellular layout. This suggests that even with a cellular layout there is still need for an online value stream mapping method to ensure that accurate lead-time numbers are generated.

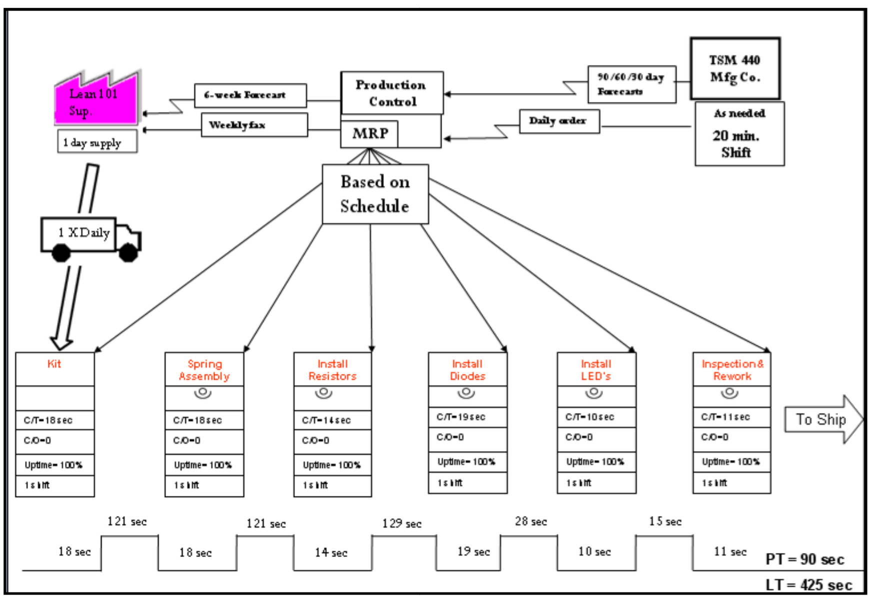


Figure 10. Cellular design VSM for Blue Avenger.

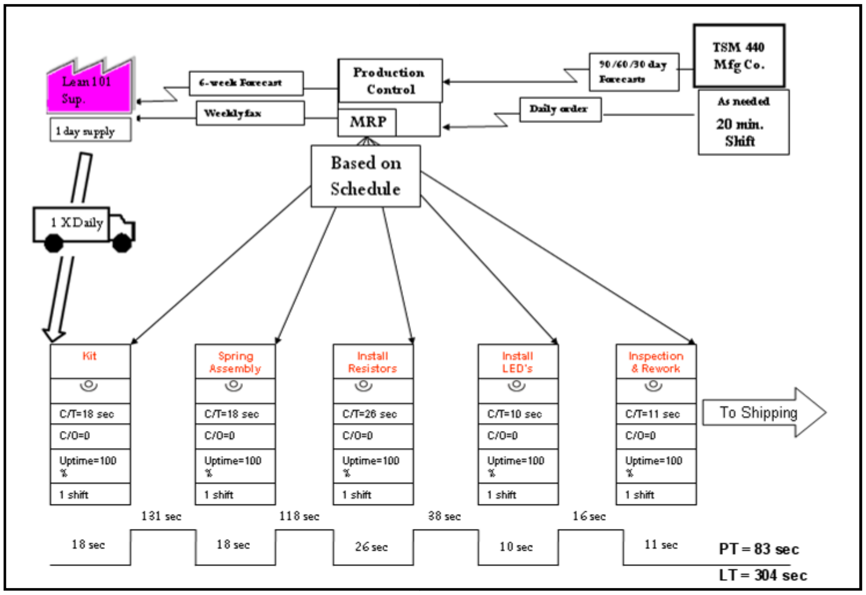


Figure 11. Cellular design VSM for Red Devil.

Conclusions

The testing showed that an RFID system can be used to determine lead times for each operation in real time. Having multiple lead times results in a more representative value stream map lead time than when using traditional value stream methods. Multiple lead times also ensures that the lead time will not be dramatically affected by the variation in inventory levels that can occur during short-term analysis.

In addition to generating more accurate lead-time numbers, RFID-based value stream mapping is able to capture the time required to move parts between operations. As testing showed, moving time can have a significant impact on an operation's lead time. The difference in moving time between the job shop and cellular layouts caused the bottleneck to shift. Testing in the cellular layout also showed that RFID antennas could be placed within 5 feet of each other before reader collision was a problem.

Lead times can be compiled into a large data file so that the company can track its lead times over extended periods of time. This data can then be used to calculate the standard deviation for each operation's lead time as well as the operation's moving time. With enough data, a normal distribution will appear and managers can be alerted when a current lead time or moving time is outside the normal range.

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CHAPTER 3: DEVELOPMENT OF A LEANNESS MONITORING SYSTEM VIA RFID: AN INDUSTRIAL CASE STUDY

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Abstract

This paper proposes a *Leanness Monitoring System* (LMS) that determines the leanness of a manufacturing facility in real-time. This LMS is composed of two main components, an *On-line RFID-based Lead-time Monitoring System* (ORLMS) and a *Leanness Prediction System* (LPS). The ORLMS determines how long a product spends in the system's inventory areas while the LPS uses this data to predict the company's leanness score. After successful laboratory testing the LMS was implemented at a local manufacturing facility, where it was used to predict the current manufacturing system's leanness score. The company received such a low leanness score that managers confidently concluded that their system needed to be improved. This prompted a series of Kaizen events to minimize the largest wastes in this system. After implementing the proposed changes, the LMS was employed again to show the managers the impact that the improvements had on the system's leanness score.

1. Introduction

Lean manufacturing has been implemented in companies around the world, because of its ability to increase the competitiveness of companies through the removal of waste. Various tools have been developed that allow tasks to be separated into value added, non-value added, and necessary but non-value added. Additionally, there are a variety of techniques created to minimize the amount of activities that are not value added so that the leanness can be increased. A great deal of time has been spent on developing lean tools that help companies make their systems leaner. However, significantly less time has been spent developing measurements that will allow a company to determine how lean a system is.

The term *leanness* has been interpreted in many different ways. Naylor et al [9] define leanness as the process of realizing lean principles while introducing the concept of "*leagility*". Comm et al [3] define leanness as a relative measure of whether or not a company is lean. They also stated that leanness is a philosophy intended to significantly reduce costs and cycle times throughout the entire value chain while continuing to improve product performance. In this paper, leanness will refer to the difference between the current manufacturing system's performance compared to the performance of the ideal state of the manufacturing system.

Knowing the leanness score of a system is important for several reasons. Firstly, a system's change in leanness scores can be used to show managers the impact that improvements have had on the manufacturing system as a whole. In addition, leanness scores can be compared, before and after improvements were made, to justify making the improvements to the system. Finally, leanness scores can be used to show managers that although the system has been improved, there is still room for further improvement. Therefore, leanness scores are able to justify the need for pursuing continuous improvement.

Several lean assessment surveys have been conceived to guide users through lean implementation [4], [5], [9]. Typically, users self-assess the leanness of their facility by either filling out questionnaires or benchmarking their company against another company that they consider to be truly lean. The gaps between the user's company and the "lean" company show the user how much leaner their company can be. Karlsson and Ahlstrom [8] created a model to assess the changes of a system towards lean production using nine groups of measureable determinants. Soriano-Meier and Forrester [13] expanded upon this model to assess the degree of leanness in a manufacturing system based upon the company's degree of adoption of these nine variables. Sanchez and Perez [12] proposed using a checklist of 36 key lean indicators to assess the company's progress towards becoming lean. Nughtingale and Mize [10] proposed a methodology that uses the *Lean Enterprise Self Assessment Tool* (LESAT). Surveys are used to compare the company's desired state of lean implementation with the company's current state of lean implementation. The resulting leanness score provides a measure of how successful the company has been in reaching their goal.

Several tools have been proposed that will allow the leanness of a system to be determined. Srinivasaraghavan and Allada [14] propose using the *mahalanobis distance* between the current state of the system and a baseline created by benchmarking other companies. Bayou and De Korvin [1] propose using benchmarking along with fuzzy logic to determine how lean a company is. Although these models deliver a quantitative leanness score, they are highly affected by the benchmark results. Additionally, benchmarking is undesirable since no two manufacturing systems are truly equivalent due to differences in equipment, people, etc. As with questionnaires, benchmarking is also subjective because the end user selects a company that they perceive to be lean. Additionally, benchmarking does not reveal if a company is actually a lean company; it only shows whether or not they are leaner than the selected company.

After talking to several manufacturing companies, it became apparent that there was a desire to know how lean a system is in an objective manner so that the results could not be altered. In addition to being objective companies wanted the end result to be quantifiable so that changes in leanness could be easily seen. To assist companies with their need the researchers then created a *Leanness Monitoring System* (LMS) which gives a quantifiable and objective measure of a system's leanness in real-time. The LMS uses an *On-line RFID based Lead-time Monitoring System* (ORLMS) to determine how long each product spends in each of the system's inventory areas. This data is used by a *Leanness Prediction System* (LPS) to predict the company's leanness score. After development, the LMS was tested and refined in a laboratory setting. After successful laboratory testing, the LMS was implemented in a local manufacturing facility, beginning with using the LMS to predict the leanness score of the current state of the manufacturing system. The manufacturing system received such a low score that the managers were convinced that their system was inefficient and needed to be improved immediately. A lean team was then formed to evaluate the manufacturing system so that major wastes could be minimized or removed. After implementing the team's proposed changes, the LMS was used again to predict the leanness of the improved manufacturing system. The changes in leanness scores showed the company's managers the impact that the team's changes had on the manufacturing system as a whole.

The rest of this paper is organized as follows. Section 2 provides information about the development of the leanness monitoring system that was used to predict the company's leanness score. Results from testing the LMS in the current manufacturing system and the company's kaizen events are presented in Section 3. Results from testing the LMS in the improved system and the team's cost justification for the kaizen events are presented in Section 4. The conclusions are then presented in Section 5.

2. The Proposed Leanness Monitoring System (LMS)

The proposed LMS consists of an *On-line RFID-based Lead-time Monitoring System* (ORLMS) and a *Leanness Predicting System* (LPS). The ORLMS is a *Radio-Frequency Identification* (RFID) system that was created to monitor inventory levels in manufacturing settings in order to determine the lead time of products as they flow through the system. The LPS then uses the lead time data from the ORLMS along with defect rates, number of operations and processing times, which are input by the user, to predict the leanness score of a manufacturing facility.

2.1 Developing the On-Line RFID-Based Lead-time Monitoring System (ORLMS)

The ORLMS was developed specifically to determine the lead time of products as they flow through a manufacturing system. As with all RFID systems, this ORLMS is comprised of three main components: an RFID tag, a reader set, and a computer with software [6]. The RFID tag and reader communicate with each other via radio signals. When a tagged item comes within the reader's *read range*, the maximum distance that the reader is able to communicate with the RFID tag, the reader tells the tag to transmit whatever information it has stored on it. Once the reader receives the information from the tag, it is sent to the computer. This can be accomplished by using cables or wireless transmitters. A computer then uses onboard software to process the information and perform its programmed tasks. The computer also uses the software to display information in a manner that can be easily read by the users.

Figure 1 illustrates how the ORLMS system interacts with the tag and computer so that a lead time can be determined. Input from the sensor is the tag status sent from the antenna to the RFID reader. A computer with onboard software records the date, time and whether or not a tag is present every minute. An example of the resulting output of this process is shown in **Figure 2.** The ORLMS then processes the input from the RFID and determines the lead time of each inventory area. This information is used to determine the overall lead time for a given product. The LPS then uses the overall lead time generated by the ORLMS along with inventory levels, number of stations, processing time, and defect rate to calculate the system's leanness score.

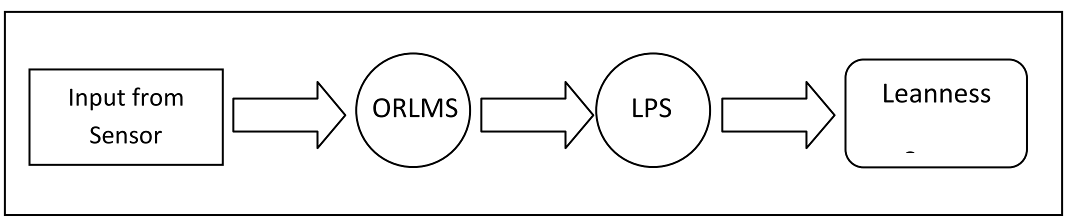


Figure 1. Diagram of the Leanness Monitoring System

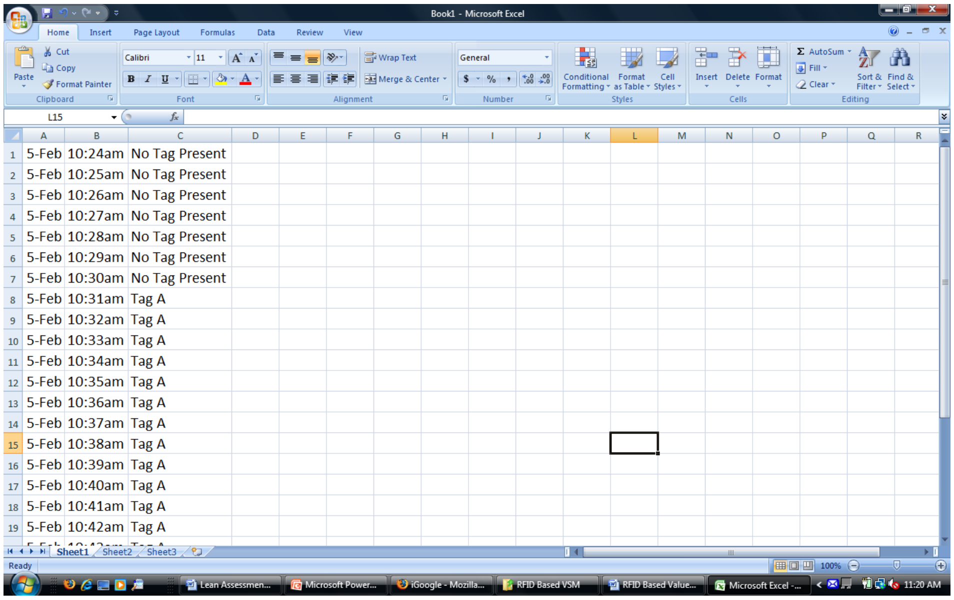


Figure 2. Output from the ORLMS System

RFID systems can consist of many readers spread across a work area or an entire facility [6]. The ORLMS system used in this case study uses four readers to monitor four different storage areas. Careful consideration was taken when selecting the components to ensure that they would be able to work in a wide range of manufacturing settings including metal-rich and water-rich environments.

Table 1. Comparison of RFID Bands Currently Used [8]

Band	Low	High	Ultra High	Microwave
Frequency	125−134 KHz	13.56 MHZ	860−930 MHZ	2.5 GHz and above
Typical Read Range	<0.5m	~1m	4-5m	~1m
Reading around Metals and Liquids	Better ⟷ Worse			
Multi-Tag Read Rate	Slower ⟷ Faster			
Passive Tag Size	Larger ⟷ Smaller			

As shown in **Table 1**, low frequency RFID readers perform the best in metal- and water-rich environments when compared to the other currently available reader frequencies. Therefore, a low frequency reader was selected because it would function well in a wide range of conditions. However, low-frequency readers typically have a read range of two feet or less, so a large gate antenna and large RFID tags were chosen to maximize the system's read range. After selecting the RFID equipment for the ORLMS, a leanness equation needed to be developed to create the LPS.

2.2 Developing the Leanness Equation Used By the LPS to Predict Leanness

A leanness prediction equation is required to convert the lead times obtained with the ORLMS to a leanness score. The researchers began this process by identifying what others had done in the past and determining the advantages and shortcomings of using each methodology. The advantages were then evaluated to see if they could be incorporated into the leanness prediction equation. Next, the shortcomings were evaluated in order to determine if solutions could be made and also incorporated into the development of the leanness prediction equation.

Charnes et al. [2] proposed the concept of *Data Envelopment Analysis* (DEA) for performance measurement using a mathematical model, which is shown in **Equation 1**. The Charnes-Cooper-Rhodes (CCR) model is a fractional program that compares the input/output variables of a set of *decision making units* (DMU's) to identify the best practices among them. These DMU's are then used to determine the benchmark for the efficiency score.

$$Max\ h_o = \frac{\sum_{r=1}^{t} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \tag{1}$$

$$\frac{\sum_{r=1}^{t} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{i0}} \leq 1, \quad j = 1,2,\dots,n$$

Where u, v, x and y are all non-negative variables

Notation:

h_o	Efficiency score of DMU_o
x_{ij}	Input Variable i of DMU_j
y_{rj}	Output variable r of DMUj
n	Number of DMU's
v_i	Weight for input variable i
u_r	Weight for output variable r
m	Number of input variables
t	Number of output variables

Tone [15] proposed using a *Slacks-Based Measure* (SBM) of efficiency as shown in **Equation 2**. The SBM is a DEA model that deals with the slacks in the input and output variables. Weights are assigned to *λ* based upon excessive inputs and output shortfalls. An efficiency score *ρ* is then computed as an invariant valued between zero and one. The resulting *ρ* represents the system's leanness score.

$$\rho = \frac{1 - \left(1/m\right)\sum_{i=1}^{m} s_i^- / x_{io}}{1 + \left(1/s\right)\sum_{r=1}^{s} s_r^+ / y_{ro}} \quad \textit{where } 0 < \rho \le 1 \qquad (2)$$

Subject to:

$$x_o = X\lambda + s^-$$

$$y_o = X\lambda - s^+$$

Where λ, s^+ and $s^- \geq 0$

Notation:

ρ	Efficiency score
x_0	Inputs of DMU_0
y_0	Outputs of DMU_0
γ	Weights for DMU's
s^+ and s^-	Slacks associated with inputs/outputs
m and *s*	Numbers of input/output variables

Realizing that a system can never be 100 percent lean Wan and Chen [16] altered the CCR model so that *Actual Decision Making Units* (ADMU) and *Ideal Decision Making Units* (IDMU) are used. Their proposed equation is shown in **Equation 3.** Cost and time are the input values used by the equation while values of the DMU's are the output variables. A software solver program was developed to calculate the leanness score.

$$Min\ \tau_{lean} = t - \left(\frac{1}{2}\right)\left(\frac{S_{\bar{T}}}{X_{TO}} + \frac{S_{\bar{C}}}{X_{CO}}\right) \tag{3}$$

Subject to:

$$1 = t + \frac{S_v^+}{y_{vo}}$$

$$tx_{TO} = \sum_{i=1}^{n} X_{Ti} \wedge_i + S_T^-$$

$$tx_{CO} = \sum_{i=1}^{n} X_{Ci} \wedge_i + S_C^-$$

$$tx_{VO} = \sum_{i=1}^{n} X_{Vi} \wedge_i - S_V^-$$

$$t = \sum_{i=1}^{n} \wedge_i$$

$$Where\ \wedge, S_T^-, S_C^-\ and\ S_V^+ \geq 0, \qquad t > 0$$

Notation:

T_{lean}	Leanness score
X_{TO}	Input time of DMU_o
X_{CO}	Input cost of DMU_o
Y_{VO}	Output value of DMU_o
n	Number of DMU_o
Λ	SBM weights for DMU's
$S_T^-, S_C^-\ and\ S_V^+$	Slacks associated with input/output
t	Multiplier

Lean is not something done in an office; it is something that is done on the production floor with workers. With such a math-intensive solution, the Wan and Chen [16] model is not practical for workers on the plant floor to use. In addition, it is easier for workers to relate to changes in time rather than cost. Unfortunately, the methodology proposed by Wan and Chen [16] uses costs to calculate leanness. Currently, there isn't a generally accepted method to transfer lead times to costs because it's not as simple as multiplying a labor rate by a time. Furthermore, some companies are hesitant to share cost information with production employees for various reasons. Therefore, a practical method of measuring leanness would ideally be done without requiring cost information.

This paper presents a simplified version of the methodology used by Wan and Chen [15] because the researchers felt that the current formula was too complicated to be used in smaller manufacturing facilities. In addition, the researchers wanted to use variables that were easier to obtain in order to increase the probability that companies would use the equation. The top of the proposed equation, shown in **Equation 4,** is set up in a similar way to the formula proposed by Wan and Chen. The main difference is that the variables are changed to ones that are easily obtainable in a real-world setting. The other difference between the equations is that the proposed equation is expanded further so that undesirable conditions are taken into account in the denominator. Therefore, undesirable conditions in the system decrease the system's leanness score, and the more prevalent the condition the more it decreases the leanness score. The proposed leanness equation focuses on the wastes as the undesirable conditions in the current system. Under ideal conditions, a one-piece flow system, the lead time of an operation would equal the system's processing time. Once again, using a one piece flow system as a point of reference, the ideal inventory level is one piece in each work station. Therefore γ and ω are calculated as the percentage of lead time and inventory that are considered wasteful. The bottom portion of the equation focuses on undesirable outputs of the current system, which in this case are defects. Therefore, ρ is the defect rate that is ideally zero.

$$Leanness = \frac{1 - \frac{1}{2}(\gamma + \omega)}{1 + \rho} \tag{4}$$

Notation:

$$\gamma = \frac{\sum_{i=1}^{n} LT_i - \sum_{i=1}^{n} PT_i}{\sum_{i=1}^{n} LT_i}$$

$$\omega = \frac{\sum_{i=1}^{n} I_i - \#\ of\ Stations}{\sum_{i=1}^{n} I_i}$$

$$\rho = \ Defect\ Rate\ of\ the\ System$$

$$LT_i = \sum_{i=1}^{n} LT_1 + LT_2 + \ldots LT_n$$

$$PT_i = \sum_{i=1}^{n} PT_1 + PT_2 + \ldots PT_n$$

$$I_i = \sum_{i=1}^{n} I_1 + I_2 + \ldots I_n$$

Where:

LT_n = Lead time of station n

PT_n = Processing time of station n

I_n = Inventory of station n

Using the proposed equation, the ideal leanness score of any system is one. However, since that can only be attained when a company uses a one-piece flow system with no defects, it is highly unlikely that a system will receive a leanness score of one. When testing the equation, the leanness score decreased very rapidly when the lead time and inventory levels in γ and ω increased up to the point where they had ratios of four-to-one. When the lead time and inventory levels used in γ and ω increased so that ratios greater than four-to–one, the leanness score started to decrease at a much lower rate. Since these ratios are low compared to what is typically seen in manufacturing facilities it is likely that companies will receive a leanness score of 0.100 or less.

After creating the ORLMS and the LPS the next step was to integrate them onto a single system referred to as the *Leanness Monitoring System* (LMS) so that the system's overall lead time could be recorded and tracked over time. This was accomplished using software developed by the researchers in Visual Basic. Once integration was complete, the next step was to test the system in a laboratory setting to ensure that the two systems would function effectively as a single unit. Testing in the laboratory showed that the integrated system was able to function as intended. Local companies were then contacted so that the system could be tested in a real-world setting with variables that may not have been previously accounted for.

3. Testing the LMS in a Manufacturing Facility

Company X is a manufacturer of woodworking equipment with facilities located in the Midwestern part of the United States. The company was started with one main product, and over the years the company has expanded their product line to include 100 distinct products. As their product line has expanded, their customer makeup has also changed. Today, their clientele is composed of big-box retailers and a network of global distributors. As the business expanded, Company X chose to conduct most of the manufacturing operations in-house rather than rely on outside suppliers to make parts for them. This allowed the company to decrease the lead time on the supply of components while also increasing the company's control over the quality of these components.

3.1 Using the LMS to Evaluate the Current Manufacturing System

Company X decided to evaluate their "KB" production line where drilling machines are manufactured, because the lead time for this product was high. The "KB" drill is currently available in two models, electric and pneumatic, in order to meet a wider range of customers' needs. The facility is currently laid out so that each product has its own assembly area staffed with sufficient numbers of employees to meet customer demand. Current demand for the KB drill is low, around 15 units per week, so only one worker assembles these products. However, at times of peak demand of 45 units per week, two employees work in the assembly area.

A team composed of the authors and Company X employees was formed to evaluate the current system. The team began this evaluation process by taking a tour of the facility, starting in the raw material storage area and ending in the shipping area. This allowed the team to understand the production processes from the company's perspective. The team then repeated the tour in reverse order to understand the how the product flows through the system from the customer's point of view. After the tour, the team drew a "process at a glance" for the KB drill which is shown in **Figure 3**. Creating a process at a glance is not only useful because it provides the team an overall picture of the production process, but it also forces the team members to agree on a representative process.

After drawing the process at a glance, the team then created a current value stream map for the manufacturing system. Value stream maps show the door-to-door flow of information and materials through the facility. It is important to note that a value stream map, as proposed by Rother and Shook [11], does not represent the system at all times. Rather, it shows a snapshot in time and represents the system at the time when the team created the map.

Lead times for each operation were obtained using the ORLMS system proposed in Section 3. To do this, an RFID tag was placed on a container of parts once they were cut on the saw. RFID antennas were placed in inventory areas as shown in **Figures 4 and 5** throughout the facility so that the time the container spent in each inventory area could be determined. The containers in the current system held large numbers of parts (more than 30), so it was common for a box of parts to be taken out of an inventory area and be returned several times before all of the parts were used. When this happened, the lead time was calculated as the difference between the time when the parts last left the inventory area and the time when the parts first arrived in the storage area.

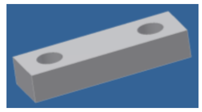
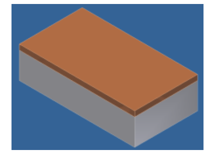
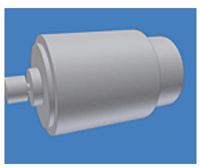
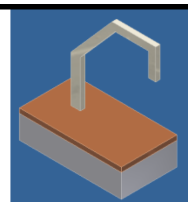
Process #	**1**	**2**	**3**	**4**
Process Sketch				
Description	Saw and De-burr	CNC	Inspection	Assemble Base
Cycle time	I min/ piece	90min/8 units	2min/unit	16 min/unit
Jig or fixture	None	None	None	None
Inspection tool	None	None	Caliper 1:8 is inspected	None
Process #	**5**	**6**	**7**	**8**
Process Sketch				
Description	Assemble Motor	Final Assembly	Package	Ship
Cycle time	36 min/unit	15 min/unit	11 min/unit	1 min/15 units
Jig or fixture	None	None	None	None
Inspection tool	None	None	None	None

Figure 3. Process at a Glance

Figures 4 and 5. Pictures of the ORLMS System Implemented in Industry

The ORLMS system does not automatically generate a value stream map; it only tracks the parts as they travel through the system. Therefore, it is important for the team to understand the steps needed to create a value stream map. The first step is to draw the production flow information for the product line being studied along the top of the map. Next, draw operation boxes for each operation in the process boxes near the bottom of the map. It is important to make sure there is enough space below the operation boxes for a timeline. Next, draw this timeline below the operation boxes, indicating processing times for each operation, as well as the lead times obtained with the ORLMS system. Finally, sum the lead times and processing times and note them in the bottom right corner of the value stream map. Following this process, the team created a current value stream map for the system **(Figure 6).**

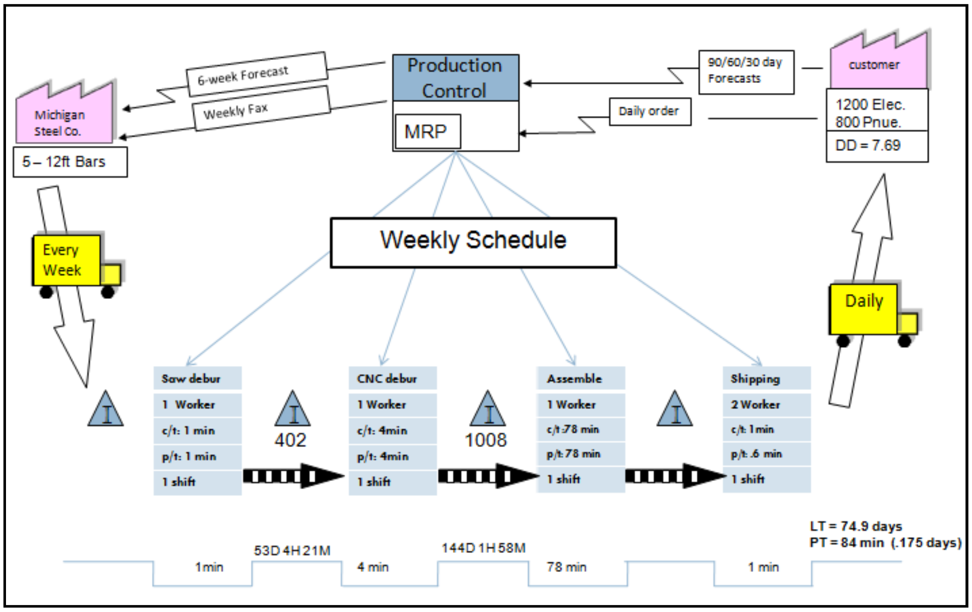


Figure 6. ORLMS-Based Value Stream Map Before Implementing Changes

3.2 Obtaining the Current Leanness Score Using the LMS

In order to determine the company's current leanness score, the ORLMS system was placed on the side of a box of parts. The "tagged" box of parts was then run through the current manufacturing system. After the box had gone through the entire system, the resulting lead times were determined, as shown in **Table 2.** These lead times represent the number of working days, hours, and minutes that passed between the time the box of parts arrived in the storage areas and when it left. When studying **Table 2**, one might wonder why there is such a large difference between the lead time in the CNC area and the assembly area. This was primarily due to the way production was scheduled at the time. Workers produced according to work orders, which did not reflect actual customer demand. In addition, it was common for workers to run unneeded parts on the CNC machine when there was downtime.

Table 2. Current Lead Times

Location	In	Out	Lead Time
CNC	3/27 8:34am	6/9 1:45 pm	53 Days 4 Hours 21 Minutes
Assembly	6/9 2:02 pm	12/19 8:44 am	144 Days 1 Hour 58 Minutes

In addition to the lead times, the defect rate also needed to be determined for this study. Workers currently record the number of defective parts that are found during production, so this was a relatively simple process. After looking through the records of defects and the number of parts that were produced in this area it was determined that the defect rate was 2 percent. After entering this information into the program, the company's leanness score was calculated to be 0.00067. The manual calculation of this value is shown in **Equation 5.** The resulting leanness score was very low, which indicates that the current system has a lot of room for improvement.

$$Leanness = \frac{1-\frac{1}{2}\left[\left(\frac{197D\ 6H\ 19M - .175D}{197D\ 6H\ 19M}\right)+\left(\frac{402+1008-2}{402+1008}\right)\right]}{1+\ .02} = \ .00076 \ (5)$$

3.3 Developing a Future Value Stream Map

After identifying what the current system looked like, the team then needed to determine what the ideal state of the system is. In addition, the future value stream map offers direction for Kaizen events that are intended to improve the current production system. The team used the eight questions proposed by Rother and Shook [11] to determine what the future value stream map would look like. Light bursts are used to highlight the largest wastes in the system, which were keeping the current system from being more like the ideal future state. The team's resulting future value stream map is shown in **Figure 7.**

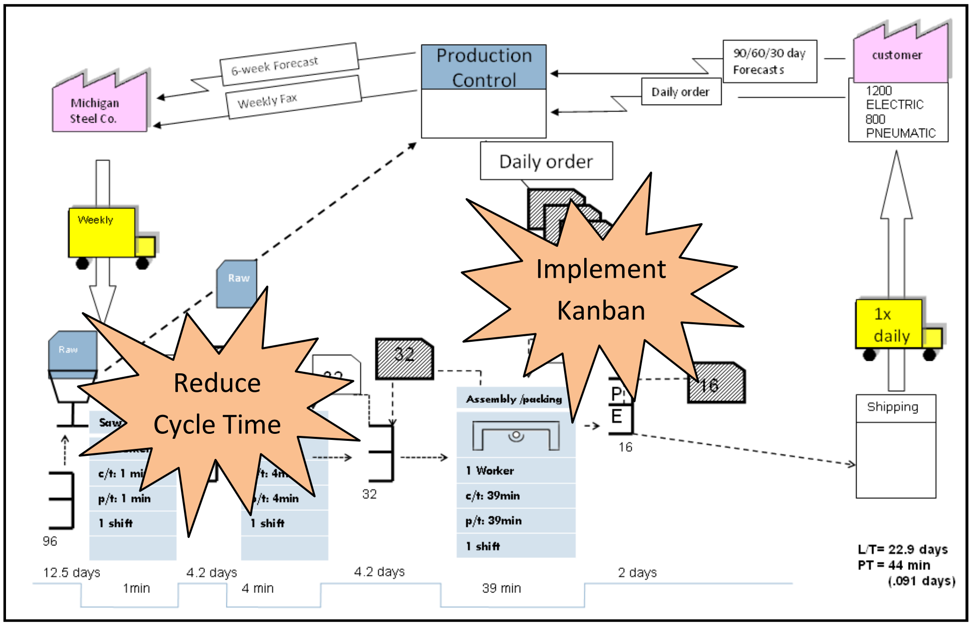


Figure 7. Future Value Stream Map with Light Bursting

Holding Kaizen Events to Remove the Largest Wastes from the System

In order for the future state to be implemented, improvements need to be made to the current system so that the indicated wastes can be removed. To do this, the team compares the current and future value stream maps in order to determine what changes need to be made to the current system to bring it closer to the ideal state as indicated in the future state map. The team's first priority is to address situations in which operation cycle times are greater than the company's takt time. Team members then need to determine the costs associated with each of the wastes and then select the most costly wastes for improvement priority.

Kaizen Event 1: Unnecessary motion in the assembly area

Unnecessary motion is a problem that relates only to the assembly area in the current system. As there are two models being manufactured in the same assembly area, there are some parts that are utilized in only one of the models and some parts that are used in both models.

After identifying the problem, the team used the "5 Why's" to determine what was causing this problem. These findings are shown in **Figure 8.**

The worker spends nearly 50 percent of the working time moving

Why?

The pieces needed for assembly are not organized.

Why?

The assembly area is used to assemble two models of a product and both models share some components. In addition, the components are stored on two shelves on the north and south sides of the assembly area.

Why?

There is not enough space to store all the components on either shelf.

Why?

The shelves are cluttered with unneeded materials.

Why

Nobody instructed employees to remove the unneeded materials.

Root Cause: There are unneeded items on the storage shelves because nobody has instructed workers to remove unnecessary items from the storage shelves.

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in order to minimize the worker's motion due to getting parts off of the shelf. A cart will be provided so that at the beginning of the work shift, the worker can go to the storage shelf and gather parts to replenish part supplies in the assembly area. As such, the worker would only have to travel for parts one time during the work day.

In order to get the most out of the POUS, the layout of the assembly area will need to be redesigned. All assembly operations are currently done on two tables, which are on opposing walls. The team suggests changing to a u-shaped cellular layout to increase efficiency. The amount of workers in the assembly cell fluctuates with the company's demand because a single worker can only assemble eight pieces per shift. However, during peak demand, as many as 16 pieces need to be completed in a single shift. In order to ensure that maximum efficiency is achieved in the new system, a *rabbit chasing system*, shown in **Figure 9,** is proposed. During the startup of the rabbit chasing system, worker “A” starts working in the tower assembly area. Once worker “A” is finished, the completed piece is carried to the next station. Once the tower assembly area becomes open worker “B” starts working in the tower assembly area. The two workers continue traveling through the system one after another. When worker “A” finishes packaging their part, they walk to the tower assembly area to start making another unit.

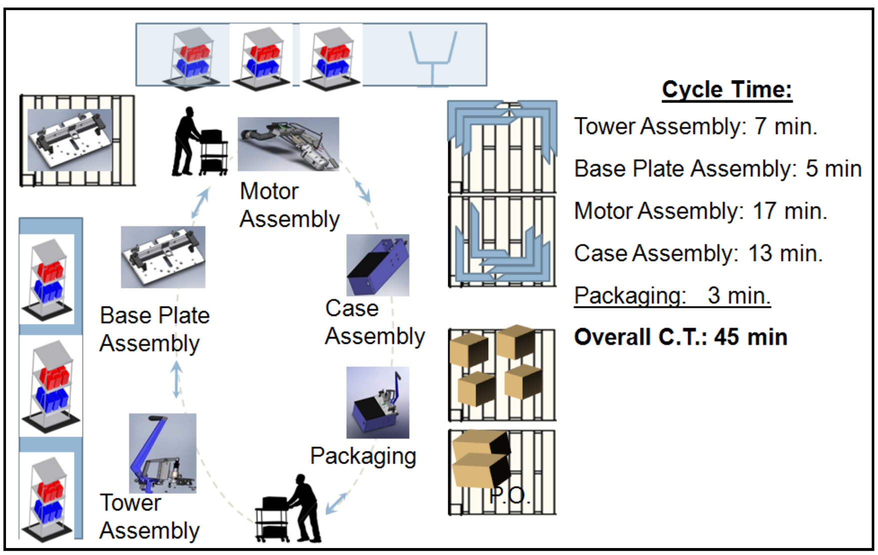

Figure 9. New Rabbit Chasing Cellular Layout

Kaizen Event 2: High inventory levels between operations

After looking at the current value stream map the team noticed that there was a large amount of inventory (144 working days) between the CNC and assembly operations. Therefore, the team decided that this needed to be addressed so that inventory levels could be reduced to a reasonable level. The “5 Why’s” for this problem are shown in **Figure 10.**

There are 301 parts waiting to be assembled.

Why?

The CNC worker machined them.

Why?

The work order instructed the worker to machine them.

Why?

The production manager created it and gave it to the worker.

Why?

Figure 10. 5 Why's for Inventory

Solution: The root cause for inventory problems is that the company's production scheduling methods allowed the production scheduler to create work orders for unneeded parts. After talking to other managers, the team found out that if the production manager forecasted a need for 30 units, he would create a work order for as many as 60 units. To ensure that this no longer happens, the team recommended that a kanban system be implemented in order to manage inventory levels. As shown in the future value stream map, the parts will be made in batches of 16 and 32 parts. This ensures that the parts can be run on the CNC machine evenly, but also ensures that a pallet can be filled with a single batch.

All of the parts travelling through the production system are currently stored in cardboard boxes that the company receives when they order fasteners, because there is no additional cost to the company. However, this results in containers that hold varying amounts of parts, depending upon the size of the parts and box. In addition, the boxes are readily available and so using them to control inventory would be impossible. Therefore, the team suggests storing parts in plastic containers of selected sizes to ensure only 16 parts will fit inside each container. Using plastic containers makes it easier for the company to control how many containers are in the system. As shown in **Figure 11,** kanban cards will be placed on the outside of each container so that workers know which part is in the container and where each container should go.

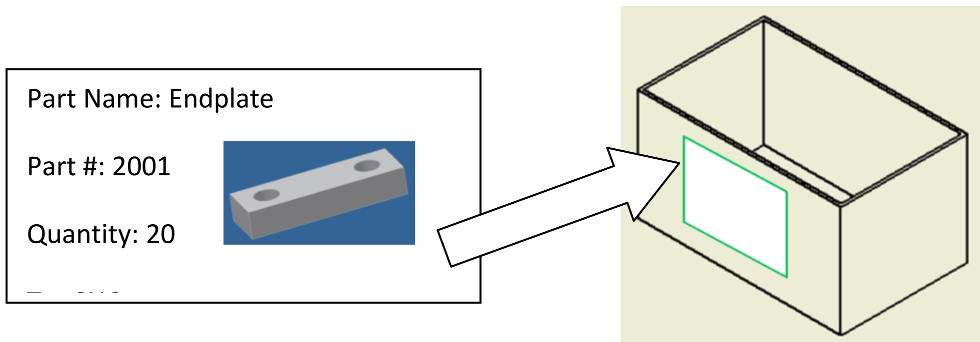

Figure 11. Kanban Card Design

In order to ensure that workers will be able to clearly tell whether or not inventory parts are needed, the team proposed that the storage areas look like **Figure 12.** When a worker needs parts, they carry their empty container and place it on the empty container shelf, or *kanban post,* which is next to the inventory shelf. A full container of parts is then taken from the inventory shelf and moved to the production area. Once an empty container is placed on the kanban post, it signals workers to produce parts to ensure that the desired amount of inventory is present.

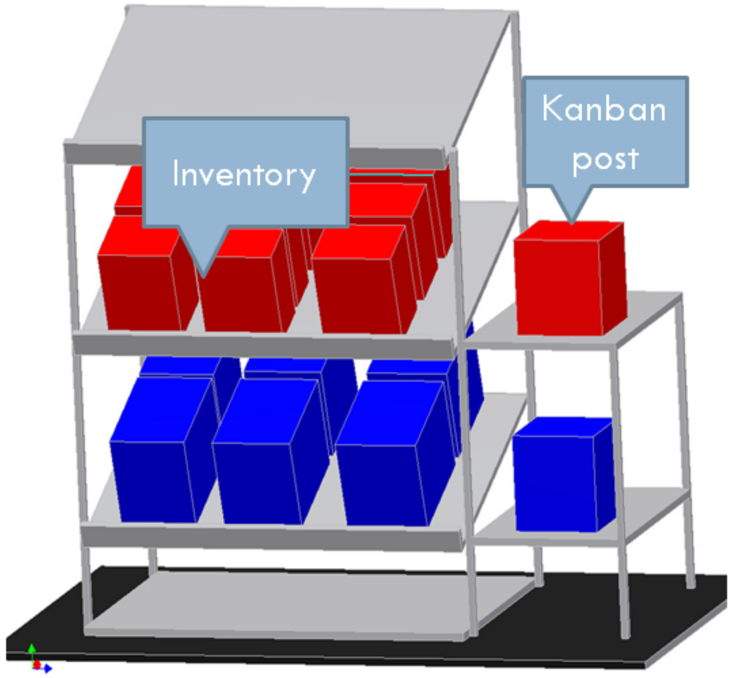

Figure 12. Proposed Kanban Storage Area

4. Using the LMS to Evaluate the Improved Manufacturing System

After determining which changes need to be made to the current system and identifying solutions to the current problems, the next step is to implement the proposed changes. After implementing these improvements, it is desirable to see the impact that the changes actually had on the system. Therefore, the LMS can be used to determine the change in the company's leanness score.

4.1 ORLMS-Based Value Stream Map with Changed System

To determine the lead times of the improved system, a box of "tagged" parts were ran through the improved system with the ORLMS in place. The lead time was determined in the exact same procedure described in Section 3, the results of which are shown in **Table 3**. Unlike in the unimproved system, where the lead times for the CNC area were significantly different, they are now only a small number of days apart. This is because the kanban system caused the inventory levels at both stations to be the same. Therefore, the lead times for both areas were relatively close to each other. The remaining difference in lead times was most likely due to a change in customer demand during testing. When testing began customer demand was approximately 40 units per week, but with the present economic conditions, customer demand shrunk to around 10 units per week.

Table 3. Improved System Lead Time Data

Location	In	Out	Lead Time
CNC	1/5 9:04 am	1/27 9:25am	12 Days 0 Hours 21 Minutes
Assembly	1/27 10:12am	2/20 2:24 pm	18 Days 3 Hours 12 Minutes

The team followed the same process described in Section 4 to create a new value stream map after the changes had been implemented. This new value stream map, with the new lead time of each operation is shown in **Figure 13.**

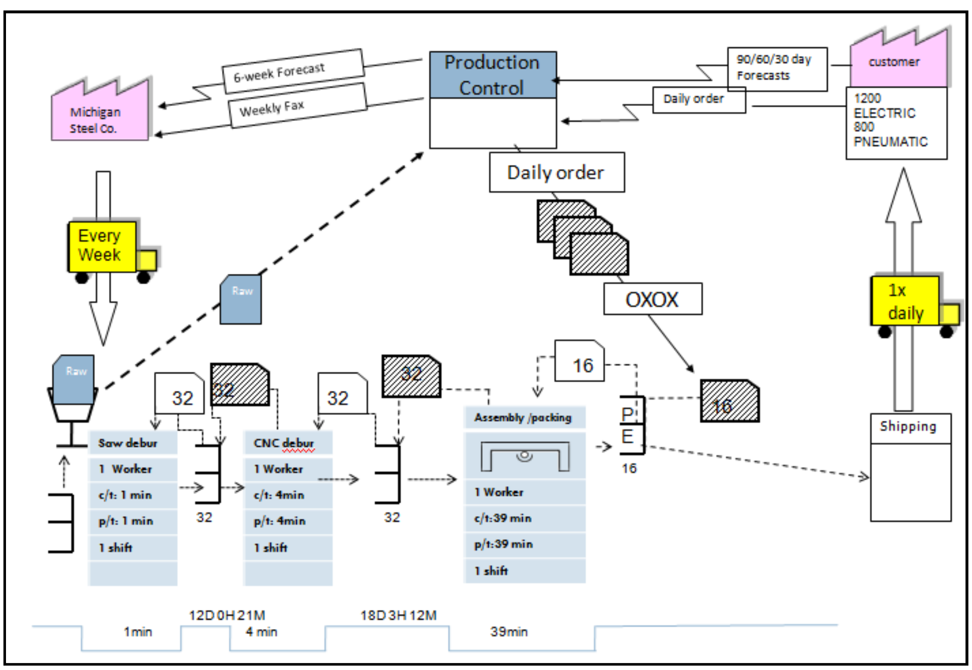

Figure 13. ORLMS-Based Value Stream Map After Implementing Changes

4.2 New Lean Assessment

In addition to the new lead times, the new defect rate must also be calculated in order to determine the company's leanness score. As in Section 3, the company's defect rate was about 2 percent. The required information was then entered into the computer program and the company's resulting leanness score was 0.01679. When comparing the company's before and after leanness scores, it becomes apparent that significant changes were made to the system because the leanness score increased dramatically from 0.00076 to 0.01679, or 2200 percent. However, the improved system's leanness score is still relatively low which shows managers there is still room to improve.

4.3 Cost Justification

After determining the change in the company's leanness score the team wanted to determine the financial impact of making the changes. Therefore, a cost justification was performed that included implementing the LMS system. The company's savings and implementation costs are presented in the following sections.

4.3.1 Savings

The cost justification began with determining the savings that were obtained by implementing changes to the system, shown in **Table 4**. In the cases of motion and rework, costs were reduced by using less labor. To calculate these costs, the team used the company's loaded wage rate of $25 per hour for each worker. The annual costs were calculated by multiplying the sum of the processing times for each part by the company's yearly demand and the company's labor rate. The amount saved indicated in **Table 4** is the yearly savings, which is simply the difference in costs between the original system and the improved system.

When calculating the inventory savings, one cannot simply take the cost of the raw materials for the new and old inventory levels because the inventory will eventually be used and thus is not being wasted. Instead, the waste is the amount of interest that could be gained if you had invested the money in either your company or another company. The resulting cost of inventory for this study is calculated as shown in **Equations 6 and 7**.

$$(Cost\ of\ Old\ Inventory - Cost\ of\ New\ Inventory)\ x\ Internal\ Rate\ of\ Return \quad (6)$$

$$[(402 \text{ x } 10.50 + 1008 \text{ x } 15.00) - (32 \text{ x } 10.50 + 32 \text{ x } 15.00)] \text{ x } 20\% = \$3{,}900 \quad (7)$$

Table 4. Yearly Savings With Implementation

Waste	Old	New	Savings
Motion	$65,000.00	$37,500.00	$27,500.00
Inventory	$3,900.00	$0.00	$3,900.00
		Yearly Savings	$31,400.00

4.3.2 Implementation Costs

The implementation costs can be divided into two main parts – the cost implementing changes to the system and the cost of the LMS. Calculating the cost of making changes was a straightforward process because it was simply the cost of labor required to rearrange the layout and remove unnecessary items from the production area. To ensure that cost to the company was minimized the system was improved during the weekend so that production was not interrupted. The existing shelving was reused so the costs for the kanban system were the cost of making the kanban cards as well as the cost of the new containers. The final cost in table 5 is the engineering cost, or the cost of the time the team spent working on the project. To calculate the cost the team members determined how many hours they spent working on the project and multiplied it by their wage rate making sure to include the cost of all benefits. The total cost of the LMS system is the sum of the costs of the individual components that comprised the system. Each of the costs as well as the total implementation costs are summarized in **Table 5.**

Table 5. Implementation Costs

Item	Cost
Change Layout	$1,875.00
Implement Kanban System	$185.00
RFID Antenna (4)	$1,583.00
RFID Readers (4)	$4,055.00
Power Supplies (4)	$400.00
Misc Supplies	$100.00
Engineering	$12,460.00
Total	**$20,658.00**

4.3.3 Overall Savings to the Company

By comparing **Tables 4 and 5** you can see that in the first year of implementation, the improvements save the company $10,742, which is the difference between the yearly savings and the implementation costs. However, in the subsequent years, the company will save $31,400 annually due to these improvements, because they no longer have to account for the implementation costs. Company X uses payback period analysis to justify all of its major expenditures and requires that all such projects have a payback period of three years or less. The payback period of this project is about eight months, which is significantly below the company's threshold. In addition, the ORLMS system has several added benefits, such as object tracking, that the company will be able to utilize at no additional cost.

5. Conclusion

Through this case study, the researchers have shown that the proposed LMS can be used in an industrial setting to determine a system's leanness score. It is also demonstrated how the leanness score of a system can increase dramatically when improvements are made to a system using lean principles. Although the manufacturing system's leanness score increased dramatically after the improvements were implemented, it is still a relatively low leanness score, which showed managers that the system still needed to be improved. The impact that the lean actions had on the overall system are as follows:

1. After implementing the lean team's proposed changes, the system's leanness score improved from 0.00076 to 0.01678 which is a 2200 percent increase.
2. The company increased their control over the amount of inventory in the system by implementing a kanban system. This allowed the company to maintain desired inventory levels throughout the system without relying on a production scheduler.
3. One of the kaizen events revealed that workers spent almost half their time walking around the work area looking for parts. After addressing this problem, the company was able to reduce the assembly cell's processing time by 58 percent, creating increased worker productivity.
4. After performing a cost justification it was determined that the payback period for the changes was 0.66 years, well below the company's threshold of three years.

In its current state, the LMS is an off-line system that requires manual calculation of lead times. In addition, leanness scores are calculated manually rather utilizing software to automatically calculate a leanness score. Therefore, in order for the on-line system to be as envisioned the following changes need to be made:

1. Continue developing the ORLMS software so that lead times can be automatically generated by the system rather than requiring manual calculation.

2. Develop software that automatically calculates leanness scores using the leanness equation proposed in Section 2.2, so manual calculations no longer need to be performed.
3. Continue software development so that the system has the ability to track multiple tags at the same time. This would not only allow companies to track multiple products at the same time, but also to track multiple containers of the same product at the same time.
4. Develop the software further so that it can automatically generate a value stream map based upon the information obtained by the ORLMS
5. Continue software development so that serial to wireless adaptors can be used. This will allow a single computer to receive signals from all the RFID reader sets rather than requiring a computer for each reader set.

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CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to develop a leanness monitoring system that would be able to create value stream maps and monitor a company's leanness score in real time. An online RFID based lead-time monitoring system (ORLMS) was proposed which allows companies to track products as they flow through a manufacturing system in order to determine the product's lead time and moving time. A leanness prediction system (LPS) was then proposed which uses the data collected by the ORLMS along with data input from the user, processing time, defect rate, inventory and number of stations, to predict the company's leanness score. These two systems were then combined into a single system, the leanness monitoring system (LMS), which monitors the company's leanness score in real time.

Findings and Conclusions

An online RFID based lead-time monitoring system (ORLMS) was proposed which allows companies to track their lead times in real-time. After completing the literature review, the components for the RFID system were selected. A low frequency RFID system was chosen because it functioned well in metal and water rich environments which are commonplace in manufacturing settings. However, low frequency RFID systems typically have a read range of two feet or less so a large gate antenna and large RFID tags were chosen to maximize the systems read range. After selecting the components, the system was assembled and tested in a laboratory setting to ensure it would function as desired. After successful testing, development was continued so the system could be enhanced further.

A leanness prediction equation was proposed which allows companies to determine the leanness of their manufacturing facility. This equation was incorporated into the proposed leanness prediction system (LPS) which allows companies to compute their system's leanness. After development of the LPS it was tested in an industrial setting. The LPS was run for an extended period of time so that multiple leanness scores could be used to ensure an accurate representation of the production system.

Kaizen events were then held to improve the production system by reducing the lead-time. The LPS was then used to determine the leanness score of the production system after the changes were implemented to determine their affect on the system.

Recommendations for Further Research

In its current state the LMS is an off-line system that requires manual calculation of lead times. Leanness scores are calculated manually rather than entering them into the LPS software which would automatically calculate a leanness score. Therefore, in order for the system to be as envisioned the following changes need to be made:

1. Continue developing the RFID software so that lead times can be automatically generated by the system rather than requiring manual calculation.
2. Continue developing the software so that it can automatically generate a value stream map given the number of processes and the lead time mentioned above.
3. Continue developing the existing software so that it can automatically calculate leanness scores so manual calculations are no longer needed. Not only does this reduce the amount of effort required by the end user, it also reduces the chance of miscalculation.
4. Continue software development so that the system has the ability to track multiple tags at the same time. This would not only allow companies to track multiple products at the same time, but also to track multiple containers of the same product at the same time.
5. Currently, each RFID reader set requires its own computer because the data is transmitted via a RS-232 cable. If serial to wireless adaptors were used, multiple readers could send signals to a single computer which would greatly reduce the amount of computers required by the system.

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